MicroArcologies: A Design Framework for Building-Integrated Greenhouses

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Abstract

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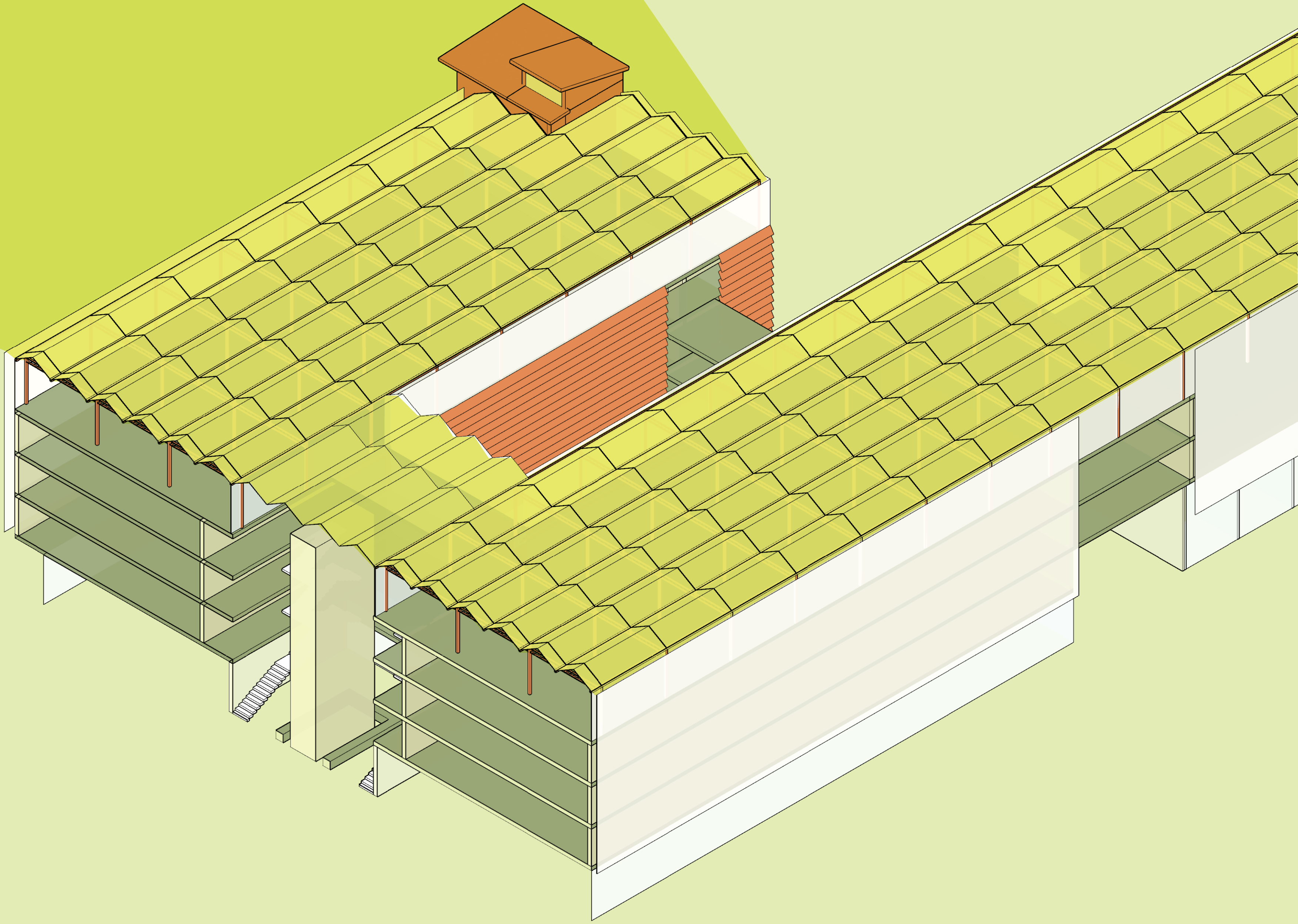
Building-integrated greenhouses are an emergent form of urban agriculture offering further decarbonization within the built environment via the creation of synergistic resource loops between controlled environment agriculture and a host building. This thesis proposes a research-based design framework for systematically assessing the design feasibility and performance strategies available to a building-integrated greenhouse project, deepening layers of value beyond basic energy and resource reduction and into a new paradigm for urban agriculture in which buildings exist as ecological adaptions of the surrounding environment. The design framework defines the key elements of greenhouse design within the built environment, including typology, structure, envelope, lighting, mechanical and control systems, growing environment, and operations. The design matrix is then applied to a selection of sites in three unique climate types, demonstrating the assessment process for determining a greenhouse integration. One of these sites is selected for a final design project, creating an opportunity to test the various design strategies in detail with a fully integrated design.

MicroArcologies

A Design Framework for Building-Integrated Greenhouses



Bryant Callahan

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Preface

Starving the Breadbasket

Starving the Breadbasket

Preface

I first encountered building-integrated agriculture after coming across Nest We Grow, a collaborative project between Kengo Kuma & Associates and the UC Berkley College of Environmental Design. Having spent most of my life in rural farming communities throughout the Midwest, I was already intimately familiar with agricultural building typologies, the conceptual nature and untapped potential of integrated agriculture set me on a new trajectory at a critical time in my education that fundamentally shaped both my perception and practice of architecture.

Regardless of the way in which architecture and agriculture stand to benefit from integration, one thing is certain: current farming practices are pushing our environment to ecological collapse. Architecture has traditionally concerned itself with the design and construction of buildings; as systems merge together and practices move into more interdisciplinary work, this creates a new opportunity for engagement with issues previously excluded from the scope of architecture. In order to accurately address these changes, it is not enough for architecture to simply adapt; architects and designers need to adopt new paradigms for their role in practice.

While the identity of the architect is strongly linked to expertise, an idea reflected in architekton, chief builder (Parcell, 2012), this is not the only role in which an architect may engage an issue spanning something as broad as architecture, agriculture, and in the case of this work, labor. Technê, the act of production which we get tekton from, is merged with archi-, not in the hierarchical sense, but as a designation of proximity: architect as one who stands closest to the act of production (Meagher, 1988). What better position to observe and learn, than at the point where the two most basic needs: shelter and sustenance, are generated? And thus, a new identity emerges: architect as advocate.

When engaging an issue encompassing multiple complex systems it is often useful to step back and first ask, why? This question may be framed in many ways, but art offers a valuable lens through which we can first engage. Agnes Denes understood the fundamental value of this in her aptly titled installation Wheatfield: A Confrontation. One glance at her portrait, standing in a field of amber grains, the skyline of lower Manhattan looming just beyond, and without any further explanation, a truth is revealed: these two things do not go together. And here, in this crack in reality, where someone as bold as Agnes tilled, planted, harvested, and distributed wheat in a place hostile to agriculture on multiple levels, and yet the questions she raised over four decades ago are just as relevant as ever. Is agriculture compatible in an urban environment?

I. Introduction

We Don’t Farm the City, Why?

We Don't Farm the City, Why?

Chapter I: Introduction

1.1 Project Overview

While building-integrated greenhouses are a relatively new typology, the concept of urban agriculture is not, with strong support and precedents within the built environment. The dissonance between the practice of architecture, which shows a willingness to engage with agriculture as it moves into the realm of urbanity, and the lack of participation from a research perspective framed a need for something to bridge the gap between these two spheres: between practice and research. A comprehensive source for understanding the complex assortment of systems and design factors involved in a greenhouse integration that could help shape and inform design strategies.

Within the current body of work on greenhouses and their use and application, there is a notable lack of engagement from architects and designers. Requests in literature for professional input from an architectural perspective are common, with topics covering a broad range of issues including support for navigating building codes while developing shared metabolic flows (Sanyé-Mengual, 2016), exploring novel forms of integrating agricultural techniques with architectural technology (Kalantari, 2017), reduction of greenhouse energy loads via passive building design strategies (Engler 2021), and examination of the aesthetic role integrated greenhouses play in urban environments (Ling, 2018; Specht, 2017). With such a need clearly identified, this thesis evolved into a framework which is by no means comprehensive, but seeks to collect the strategies, technology, and design guidelines for greenhouse integration and organize them into one place.

Literature Review

A qualitative literature review on the design, operation, and application of greenhouses examines what opportunities, tools, and processes are currently available to designers. This information is framed and organized through the lens of architectural practice, which also examines emerging areas of research to consider innovative ways of thinking about greenhouses to better inform the way we as designers include them in projects.

Design Framework

From the literature review, the findings were organized and contextualized into something that could serve as a design tool. An integrated design matrix, which helps architects and designers make informed decisions about the form, arrangement, and function of an integrated greenhouse project. This tool provides a systematic workflow for assessing a site for potential integrations and then formulating a strategy with considerations to the various factors that arise with the addition of a greenhouse component.

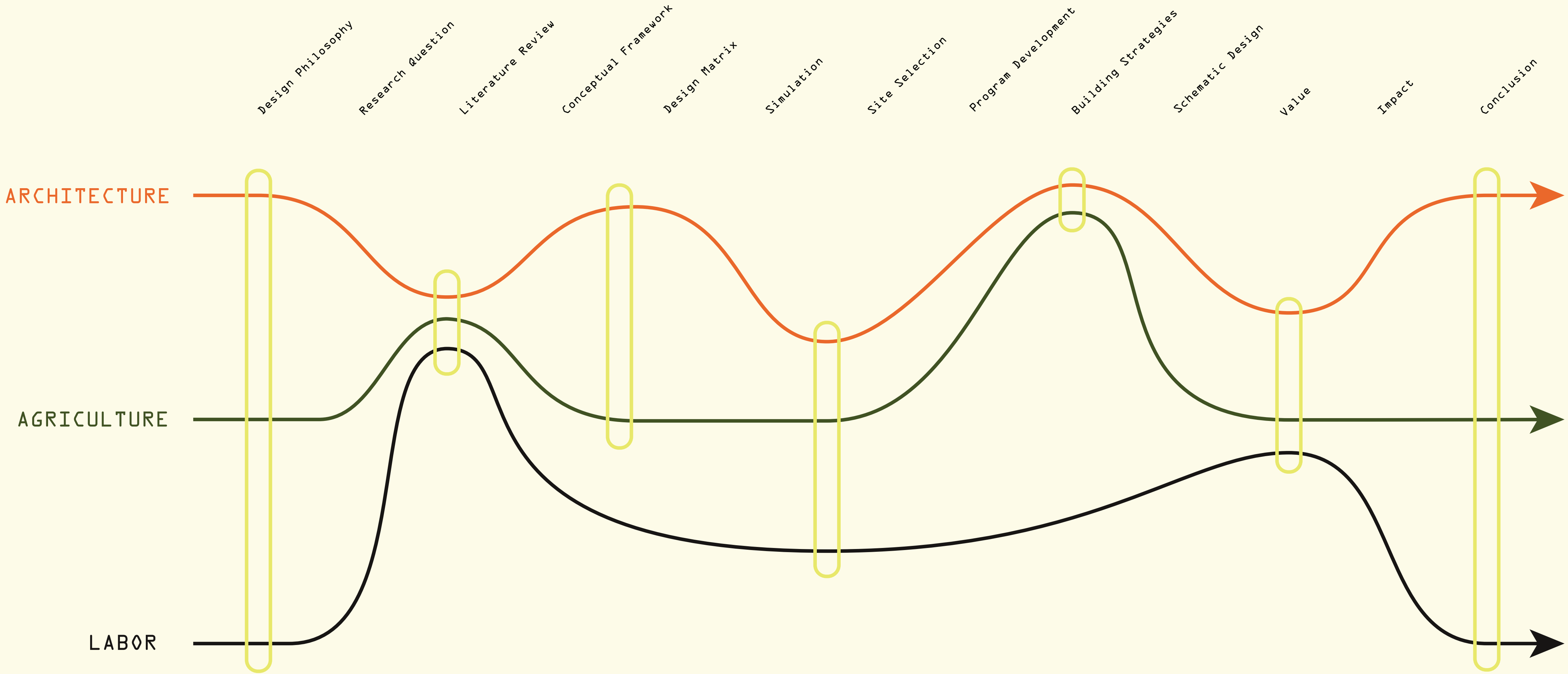
Applied Design

In order to test the framework, the last component of this project applies the it to a specific site. Starting with a broad examination of potential regions, the framework guides a series of design decisions that lead to an integrated greenhouse design in Tucson, Arizona, where the process of selecting and applying a collection of design strategies culminates in an example building: The MicroArcology.

Fig 1.1 : Wheatfield - A Confrontation. Agnes Denes, 1982

Research Question

“What are the essential factors to consider when integrating a greenhouse into a building design?”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Value
Impact
Conclusion
ARCHITECTURE
AGRICULTURE
LABOR

Fig. 1.2: Scope

1.2 Research Question

This chapter opens by asking why we don't farm the city, or perhaps phrased more explicitly, questions why we don't grow our food in the same place we eat it. While there are a number of assumptions that undoubtedly arise as an immediate response to that question, this project isn't about the straightforward answers, but about looking at something and asking how it might be different, and if so, what the conditions necessary to explore that difference might be?

Agnes Denes did exactly that when she planted a wheat field in Manhattan in 1984 (figure 1.1). There may be plenty of reasons for why we don't farm the city (although this work is evidence that may be changing, given the trends in urban agriculture that will be discussed later), but take one look at ripe heads of wheat growing in the shadow of a string of towers and while not clear, the dissonance of those two elements together suggests that the reasons we grow our food in rural areas, and the subsequent separation between agriculture and urban culture, is much deeper and older than we might first suspect.

While it's useful to ask why, that question is only the starting point. In order to propel the question toward something that allows for actionable steps to be taken, this work asks what the essential factors to consider are when integrating a greenhouse into a building design, and then looks for a way to organize and share those factors in a systematic, accessible method.

1.3 Scope

Greenhouses represent a complex collection of environmental control systems organized around the production of plants and their various byproducts, including fruits, flowers, and clones of the same plants. While many of the systems utilized in greenhouse share overlap with the built environment, due to the specialized function of greenhouses, research on their use and application extends a broad range of topics including horticulture and biology. Additionally, this project is focused on the integration between architecture and agriculture, each of which represent entire fields of study on their own.

Because this project develops a theoretical framework for understanding greenhouses through the lens of architecture, the design process shares many similarities to that of any other building, with the exception that instead of people, the internal environment is optimized for plants. Greenhouses are used to cultivate many different species of plants, but since a core component of this framework centers around urban agriculture, for the scope of this project the discussion will be limited to greenhouses used in an agricultural capacity for food production. However, while agricultural greenhouses represent a common application for their use, in order to develop an accurate understanding of greenhouses with potential for building integration, the literature review examines greenhouses in any use, including those dedicated solely to ornamental plants or flowering products, such as cannabis.

Only when the conversation shifts from the literature review to the design framework does it become necessary to narrow the scope to define only greenhouses engaged in controlled environment agriculture (CEA) that implement a soilless growing method. By focusing the scope, we are able to emphasize that modern greenhouses are technologically advanced and complex structures which must meet the same standards as the building codes of their host building, which rules out most soil-based or non-controlled variations. This also accepts that, due to their complexity, the cost of constructing a CEA greenhouse remains a significant challenge for any design, and thus the need for a stable production environment becomes an important factor. CEA offers the most efficient and stable return on investment within urban agriculture, and represents the current best practice for this sort of project.

Regarding Labor

Over the course of this research, an unexpected topic emerged around the topic of greenhouses and their relationship to labor. While the connection between architecture and agriculture is the primary relationship examined throughout the course of this work, agriculture is connected to farming, and farming implies labor. Labor, while not originally in the scope of this work, emerged as a notable factor in much of the current research, especially related regarding the role of climate in the investment of greenhouse infrastructure. There is not sufficient resources to fully explore the emergence of this issue, nor should it shift the focus away from developing an integrated design framework.

However, since this project deals with agriculture, it is by proximity also inherently tied to labor, and thus worth addressing in the scope. The topic was first noted during the literature review, but only fully became apparent late in the final stage of this thesis, where labor conditions in Arizona are related to the lack of greenhouse infrastructure, a theme seen in other regions with similar climates (Pardossi et al., 2004). What and how exactly this relationship looks like related to the design process is unclear; it's simply worth noting that it plays a vital role, and that future integrations should address the fact that designing a greenhouse means there needs to be labor to staff that greenhouse, a complicated topic in urban settings where perceptions about farming are often incompatible with ideas of urbanity (Sanyé-Mengual, 2016). The place where the topic of labor could be explored within this project was the applied design, which takes on a social component that considers what mixed housing and a cooperative produce distribution space could look like paired with an integrated rooftop greenhouse, in hope that by presenting a chance to think differently about how urban agriculture is practiced will help daylight future work around the connection between labor and urban agriculture, further supporting better greenhouse design in the process.

1.4 Deliverables

Three deliverables were defined as an outcome of this work, each of which build and expand on the previous one to take the topic of greenhouse integration from it's current state into a theoretical framework, and then into an actionable design workflow before being finally realized as a proposed building concept.

Literature Review

A literature review covering current research related to greenhouses, which includes a historical context of the evolution of greenhouses up the modern versions we have today, sections on terminology and typology, as well as sections for each of the major components of a greenhouse: structure & envelope, lighting, HVAC, and irrigation and climate control systems. This portion not only condenses all the various research across multiple fields into a single document, but contextualizes it for designers and architects in order to create an accessible entry point into the topic.

Design Framework

From the findings of the literature review, develop an integrated design framework. The framework will serve as a series of steps meant to guide a designer unfamiliar with the intrinsic needs of a greenhouse through the process of integrating one into a building design. Because every architectural project is unique, rather that a set of rules, the framework might be thought of as a toolbox of components, all of which have been validated and share a strong connection to greenhouse design.

The order of these tools allows designers to enter with either a proposed project or, test a theoretical project, examining how designs and strategies could work together to understand the introduction of integrated agriculture as a deeper way of engaging in the design process. A mode of working which understands the building and its product as a direct expression of the surrounding context.

Applied Design

The best way to test a framework is to apply it, so for the third and final deliverable of this project, the focus shifts from theory to practice. Following the sections laid forth in the design framework, a series of climates represented by three distinct cities in the US - Seattle, WA, Chicago, IL, and Tucson, AZ - are considered in the context of design goals and program development. With the support of some initial cost simulations, one site is ultimately selected and then a proposed building is developed from program all the way to schematic design, focusing on responsive strategies that arise as the result of applying the design framework to the process.

This building, named the MicroArcology, is not so much an emphasis on architectural technique as it is an opportunity to explore where architecture could go if agriculture is expressed as a governing element of the design process, rather than a value addition to an already developed building design.

1.5 Outcomes

As it stands, agriculture is at a crossroads. Each year that passes trends growing in controlled environments move upward, while at the same time, the physical environments housing these operations move closer and closer to urban areas (Benis et al. 2017). The collision of architecture and agriculture is not hypothetical, but already upon us. The question now is not if, but what are going to do with this change?

In thinking about designing with greenhouses, we have an opportunity to re-examine our relationship with the built environment by considering that the needs of another species, of plants, might need to share a space for thriving. This challenge is exactly that, and while the deliverables in this project are intended to support the exploration and application of an integrated greenhouse design, the doors it opens along the way are just as profound: to be afforded a glimpse at looking at where our food comes from, and where we consume it leads to larger questions and helps anchor us as designers to larger issues which cannot be solved, but are inevitably part of and will shape with our actions, now and in the future.

II. Literature Review

Framing the Issue

Framing the Issue

Chapter 2: Literature Review

2.1 Development

The earliest documented instance of greenhouse construction is found in the first century CE, when Roman agricultural writers Lucius Junius Moderatus Columella and Gaius Plinius Secundus (Pliny the Elder) describe a prototype greenhouse, a specularia, built for Emperor Tiberius so that he could enjoy a favorite melon year-round. The greenhouses were constructed as wheeled planting beds covered with frames glazed in transparent stone, likely mica or lapis specularis (Paris et al. 2008). The beds were rolled outside on sunny days, and when it was cold or during winter, they were retracted back into the frames for year-round growing.

Although the idea of harnessing year-round growing capability is not a new concept, the ability to artificially control light and temperature separate from the external environment was not accessible until after 1700, when glass making technology transitioned to a pouring process and became cheaper and more accessible. Early greenhouses built around this time were typically masonry, wood, or stone structures with large window openings integrated into the facade, now a feasible option due to the availability of plate glass [cite]. However, it wasn't until the turn of the 19th century when iron became widely available that buildings closer to the form of our modern greenhouse began to appear (National Gallery of Art, n.d.). These iron and glass structures opened up new possibilities for design, largely due to the ability to construct wide-span, filigree, and eventually multi-span buildings which had previously been impractical or impossible to construct using stone or wood (DeFacio 2002).

The term greenhouse also rose to prominence during this period of development and was often used interchangeably with synonymous terms such as hothouse and conservatory, although there was some effort to distinguish between them, such as prescribing greenhouse to plants grown in pots, while conservatory was for more mature plants placed in soil beds, and hothouse was a specific location of the greenhouse or conservatory which was heated and warmer than the other areas (National Gallery of Art, n.d.). The need to accurately define and specify a building's relationship to agriculture is something still reflected in the language we use today, and just as with the early terminology, we are still working to find the best way to describe spaces made for housing and growing plants.

During the 19th century, greenhouses grew in popularity among wealthy individuals who wanted to bring exotic plants from tropical climates to their homes in cooler climates such as France, England, and the Netherlands. These structures were open in plan and often divided into areas based on the type of plant being grown inside, which allowed for different areas to be zoned based on the preferred heat and light of the occupants. This specialization eventually led to the development of early greenhouse typologies, which retained the typical structural arrangement, but altered the facade and roof shape slightly to best serve the desired plantings inside, as was the case with the vinery, orangery, and palmhouse (National Gallery of Art, n.d.).

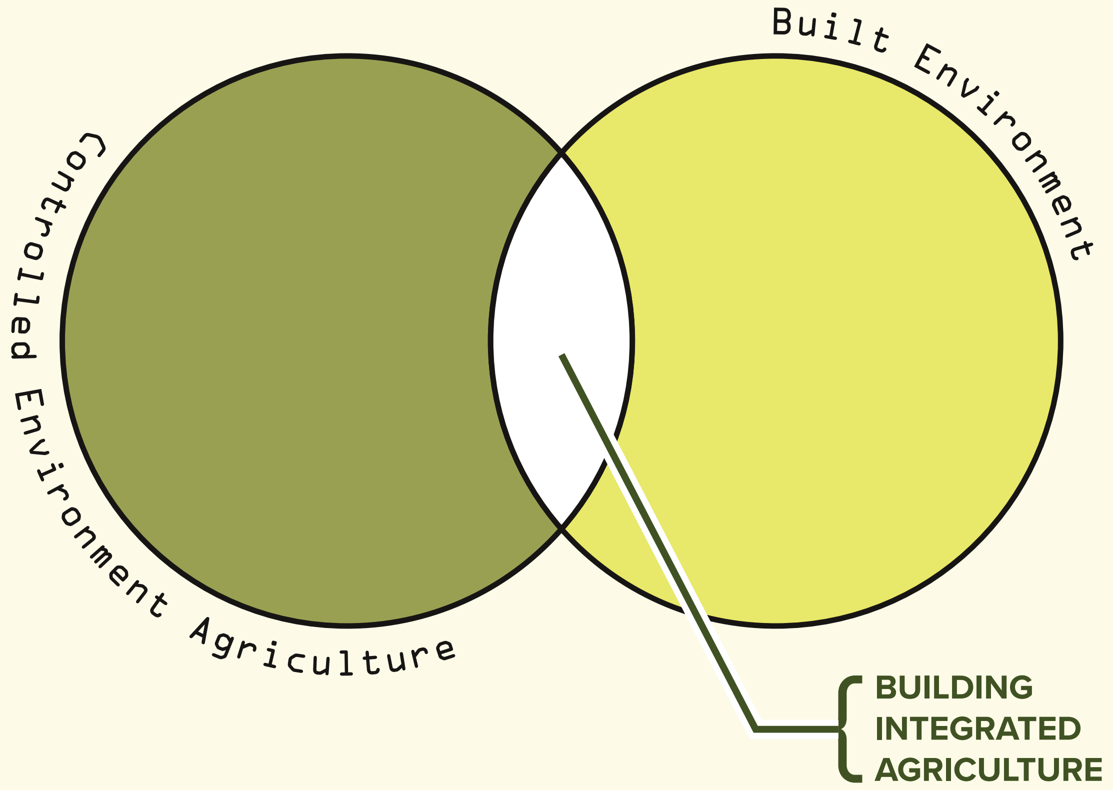


Fig 2.1: Blended Environments

Modern Greenhouses

With the established concept of the greenhouse as a space for controlling the environment as a means for plant growth and production, further development branched into two directions, driven largely by climate and material choices. With plastic becoming widely available by the 1960s, Greenhouses built in warmer climates, specifically those in Mediterranean areas, were primarily developed as low-cost, naturally ventilated structures that extend the current growing seasons (DeFacio 2002).

In the other direction, cooler climates such as the Netherlands embraced the growing use of controlled environment agriculture, which when paired with a high-tech glasshouse, could provide a stable year-round growing environment. However, the use of plastics and lightweight metal allows alone was not enough to bring widespread adoption; this coincided with another important development, this time related to agriculture. The development of modern hydroponics systems, pioneered by Dr. William Gericke at the University of California, Davis in the 1930s opened an alternative strategy to farming

Although the development of hydroponics represented a critical component in the adoption of greenhouses, it was the larger application of closed environment agriculture (CEA) that demonstrated the real capabilities of greenhouse use. As Despommier notes, though farming technology continued to advance, up until CEA the basic practice of agriculture remained the same: dig, plant, fertilize, irrigate, weed, harvest, sell (Despommier 2013). CEA represents a new way of approaching agriculture, driven by the technological advancements of greenhouses, which when fully enclosed allow for year-round growing conditions in even the most hostile environments (McCartney et al. 2018).

By the 1980s, the Netherlands had established themselves as expert commercial growers with closed environment greenhouse agriculture (DeFacio 2002), which led to many Dutch greenhouse manufacturers constructing greenhouses primarily in the surrounding areas in Europe (McCartney et al. 2018) and later, North America (Nadal et al. 2017). While beyond the scope of this review, it is important to note that the documented benefits of closed environment agriculture are extensive, including zero-agricultural runoff, significantly less water consumption and increased growing cycles per year (Despommier 2013). Important to this discussion is the relationship to the built environment: closed environment agriculture is considered a form of protected agriculture, making it ideally suited for hostile environments, including urban settings (McCartney et al. 2018).

Relationship to Urban Agriculture

With the adoption of closed environment agriculture and the accessibility of new materials, greenhouses started appearing in industrial areas within cities, where previously they had been confined to peri-urban sites where land was still relatively affordable (cite). By taking advantage of vacant rooftops, vertical spaces, and unused warehouses, urban agriculture expanded from simple, community soil-based gardens to full-scale commercial growing operations. This phase of development occurred inside densely populated urban areas where vacant rooftops and building facades offered new opportunities for the location of food production systems, often designed to exploit natural synergies between agriculture and buildings (Thomaier et al. 2015). With this recent development, the conversation and topics around greenhouse research are shifting to integration in order to best understand the relationship and potential benefits these two structures share, especially as modern,especially as modern, closed environment greenhouses require a significant amount of energy and water to operate (Zisis et al. 2019).

2.2 Terminology

The use and application of closed environment agriculture greenhouses into the built environment represent the primary area of growth in urban agriculture. However, like many new and innovative areas, the terminology used to describe the relationship between greenhouse, building, and environment are varied and often inconsistent. In order to develop a framework for understanding this complex issue, it is important to first understand the key terms used to define urban agriculture, as well as the associated subtypes relevant to buildings and building integration.

Freestanding vs. Gutter-Connected

At the most basic level, greenhouses are classified as either freestanding or gutter-connected. Freestanding greenhouses are comprised of a single bay, usually with a gabled or curved roof, and walls on either side and ends. In contrast, gutter-connected greenhouses consist of an array of these singular bays running side by side, the interior walls of each bay absent except for the outermost exterior walls, and a shared gutter linking each set of adjacent roofs. However, in the context of urban agriculture, the use of the word freestanding can be somewhat problematic as it implies that the greenhouse exists apart from any other structures. This is not the case, as many freestanding greenhouses are connected to other building forms on the ground level, or in the instance of rooftop greenhouses (RTGs), situated on top of a building. The important difference between these two taxonomies is the use of a singular vs. linked bay system. The typical span of each bay and roof pitch are similar, while the length is determined by the size of the site or roof. The critical difference between the two systems is the height, which can be increased significantly in gutter-connected greenhouses due to better structural stability against wind loads, especially in configurations larger than three typical bays (Fernández-García et al. 2020).

Basic Configurations

In order to effectively examine the relationship between greenhouses and urban agriculture in the built environment, it is also necessary to establish a theoretical framework for defining the different configurations a greenhouse might take given these parameters, then selecting only those which fit within the proper scope. Greenhouses represent a wide range of configurations, from a simple, low-technology hoop tunnel sitting on bare ground, to a fully enclosed, climate-controlled glasshouse. Goldstein et al. (Goldstein et al. 2016) developed a useful matrix for understanding the relationship between greenhouses, urban agriculture, and the built environment.

While greenhouse may fall into any one of these four categories, the two most relevant to the built environment are the building-integrated categories, commonly lumped together in the context of urban agriculture under the general term of building-integrated agriculture (BIA) (Caplow 2007, Appolloni et al. 2021, Buehler et al. 2016).

Ground-Based, Unconditioned	Ground-Based, Conditioned
Building-Integrated, Unconditioned	Building-Integrated, Conditioned

Fig. 2.2: UA Types,
Goldstein et al. (2016)

Building-Integrated CEA

In the field of building-integrated agriculture (BIA), closed environment agriculture (CEA) represents the greatest potential: greenhouses are complex, expensive systems, and as noted above, CEA operations mitigate losses, lowering the risk of adoption and extending the operational growing season. When added to a new or existing building project, this becomes a critical factor for further adoption. However, there is currently some discrepancy regarding the terminology used to specify these systems. The term BIA itself was coined by Eric Caplow in 2007 (Specht 2017) in reference to an integrated greenhouse system that, when paired with an existing building, developed a symbiotic relationship. Now, the term is used generally, as an umbrella descriptor for a number of subcategories that have become more specific as urban agriculture grows in popularity.

Like many other areas of innovation, new terms were developed and popularized by certain groups to refine this definition to be more specific, such as zero-acreage farming (ZFarming), which shifted the value from system to social issues, specifically those arising from globalization (Thomaier et al. 2015). Other terms more specific to building integration eventually came into use, such as vertical configurations (vertical farming) (Despommier 2013), which extends the definition beyond greenhouse to conditioned interior grow spaces with artificial lighting. These terms continue to fragment as the level of specificity increases, such as the distinction between RTGs and integrated RTGs (i-RTGs) (Muñoz-Liesa et al. 2021), which are rooftop greenhouses integrated into a building on a systems-level to form a symbiotic relationship.

2.3 Typologies

Greenhouses are typically classified by their roof shape (Dalai et al. 2020, Badgery-Parker 1999), a practice that started with their historical development and still continues today. As discussed in the introduction, the earliest greenhouses were essentially containers for wealthy individuals wanting to showcase their exotic fruit collections, and thus took on specific forms optimally suited to the products grown inside, with naming conventions reflecting those consequential typological forms (orangery, vinery, pinery, etc (DeFacio et al. 2002, USBG, n.d.). Although roof shape is still the most prevalent taxonomy, the rise in commercial adoption meant that greenhouses, while still expensive, were no longer the exclusive domain of wealthy individuals. In addition to roof shape, the level of investment became another common method for classifying greenhouses ranked by low, medium, and high technology (Ruijs et al. 2020, Dalai et al. 2020). This method has both advantages and disadvantages compared to the roof type method. For example, while useful for general planning, the level of investment often makes assumptions about the structure, operations, and systems that are available to

Category	Enclosure	Building-Integration	Symbiosis	Sources
Building-Integrated Agriculture	Covered/Enclosed	Any	Potential	Caplow (2009)
Vertical Farming	Covered/Enclosed	Vertical	Potential	Despommier (2013)
Skyfarming	Covered/Enclosed	Rooftop	Potential	Germer et al. (2011)
ZFarming	Open/Covered/ Enclosed	Any	No	Specht et al. (2014.
Urban Rooftop Farming (URF)	Open/Covered/ Enclosed	Rooftop	Potential	Buehler (2016)
i-RTG	Closed	Rooftop	Yes	Muñoz-Liesa (2021)
Containerized Food Production System (CFPS)	Closed	Ground/Rooftop	No	Wilkinson (2021)

Fig. 2.3: Building-Integrated Agriculture Terminology

that typology, limiting the ability to accurately compare and describe different systems, such as classifying the structural use of wood as a low-tech typology (Teitel et al. 2012, Dalai et al. 2020).

While this is certainly true in many instances, from a design standpoint, wood may be a viable option for structural columns in a fully enclosed glasshouse (high tech). Additionally, as urban agriculture grows in adoption, greenhouses are frequently becoming integrated into building spaces, creating an additional layer of investment that may or may not reflect the actual form of the greenhouse itself.

The growth of urban agriculture, supported by the broader advancements in commercial growing, have led to a new typological method of defining greenhouse forms based on their level of enclosure (open/partially enclosed/closed environment) and relationship to surrounding structures (free-standing/connected/integrated) (Teitel et al. 2012, Goldstein et al. 2016, O'Sullivan et al. 2019). This method provides numerous advantages for disciplines within the built environment that may be concerned with technical aspects of greenhouse design. However, like the investment typology, the terms used to describe a greenhouse using this method still vary greatly due to a lack of consistency in how greenhouses connected to buildings are both described and constructed, as already addressed in the terminology section of this paper.

In order to establish consistency for the scope of this review, greenhouses will be classified by roof shape, which continues to provide the most accurate parameters for describing a given form, namely the span of the roof, or in the case of multi-span greenhouses, the module, and determines the growing bay width and height. Regardless of any aesthetic, performance, or other benefits that might be gained from a greenhouse, it is first and foremost a utilitarian structure defined by a single metric: the capacity to grow things in a controlled or semi-controlled environment different from open agriculture. The roof shape has the most direct impact on the capacity of the greenhouse to accomplish this (Dalai et al. 2020), and thus will serve as a useful tool for classifying the various forms a greenhouse may take to accomplish this goal.

Results show that uneven-span shape greenhouse receives the maximum and Quonset shape receives the minimum solar radiation during each month of the year at all latitudes. East-west orientation is the best suited for year-round greenhouse applications at all latitudes as this orientation receives greater total radiation in winter and less in summer except near the equator. Whist, Chandra et al [4] argued that north-south orientation results in better homogeneity of the microclimate for northern climatic conditions in India. While, Dragićević [5] concluded that, for uneven-span greenhouses orientated east-west and north- south (as comparison) at different latitudes at the northern hemisphere of Belgrade, Serbia, the east- west orientation of uneven-span solar greenhouse is the best suited during each month for all examined latitudes.

Level	Covering Material	Environmental Control
High-tech	Plastic	None
Mid-tech	Plastic	Limited
Low-tech	Mainly Glass	High Degree + Automation

Fig. 2.4: Greenhouse technology levels. Rujis (2018)

Flat Roof Types

Flat (Parral/Almeria): The flat roof, typically with a slope of less than ten degrees, is typically constructed of plastic film stretched over a series of continuous tension wires (Elsner et al. 2000). This type of roof is often referred to as a Parral or Almeria type greenhouse, as it is generally only found in the Almeria region of Spain.

Even Span (Gable): The even span gable roof is one of the most common roof types (DeFacio et al. 2000) as it allows for more usable space than many other roof types, can be lengthened to accommodate wider bays if necessary, and provides good natural air circulation and stable temperatures (Badgery-Parker 1999). A typical configuration is a galvanized steel Fink truss set on steel columns.

Uneven Span: The uneven span is used on hillsides where southern exposure allows it to capture more light during winter due to one side of the roof is longer than the other (DeFacio et al. 2000), improving the surface where an ideal incidence angle occurs. While these greenhouses are ideal for hilly or sloping terrain, they cannot be automated due to the difference in height, and thus are not as popular (Dalai et al. 2020).

Venlo: The Venlo style, also called a ridge and furrow greenhouse, has become one of the most commonly used roof typologies, largely due to the ability to use less material for a greater span and more available light to the growing space below. The Venlo greenhouse consists of two or three low-profile gables running along a flat truss. These bays are arranged in parallel and connected at the gutters, which contain a structural member running perpendicular to the truss system (Muñoz-Liesa 2021). The term Venlo itself originates from the area where they were developed in the Netherlands and has come to be used synonymously with gutter-connected, high-tech glasshouses (DeFacio et al. 2000). It is import-

Roof Type	Sources
Flat (Parral/Almeria)	(Elsner et al. 2000)
Even Span (Gable)	(DeFacio et al. 2000, Taki et al. 2016, Proksch 2017, Badgery-Parker 1999, Nelson 2014)
Uneven Span	(DeFacio et al. 2000, Taki et al. 2016, Dalai et al. 2020, Nelson 2014)
Venlo (Ridge & Furrow)	(Proksch 2017, DeFacio et al. 2000, Goldammer 2019, Muñoz-Liesa 2021)
Vinery	(Taki et al. 2016)
Lean-to	(Dalai et al. 2020, DeFacio et al. 2000, Nelson 2014)
A-Frame	(DeFacio et al. 2000, Nelson 2014, Goldammer 2019)
Semi-Solar (Skellion)	(Badgery-Parker 1999, Taki et al. 2016)
Sawtooth	(Badgery-Parker 1999, Proksch 2017, Goldammer 2019)

Fig. 2.5: Flat Roof Typologies

ant to note that sometimes the term Venlo will be used as synonymous with gutter-connected, however, Venlo denotes the roof shape while gutter-connected refers to the structural arrangement. Most Venlo greenhouses are gutter connected, as the true benefit of this typology is found in the larger greenhouses where the bays can span to ten bays or beyond. However, not all gutter-connected greenhouses are Venlo style, with sawtooth or even gable spans also being used at times.

Vinery: The vinery style roof is a high pitched roof with low, sloping walls (Taki et al. 2016). This type of roof, once a historical archetype important in the development of the greenhouse (National Gallery of Art, n.d.) does not offer the scalability or benefits of some newer types, and thus is regulated to low-tech, region-specific uses.

Lean-to: Lean-to greenhouses consist of a single slope attached to a building on the high side, limiting the available span compared to other types (Dalai et al. 2020), or in some cases, a thermal mass used to absorb solar energy for passive temperature regulation at night (Taki et al. 2016).

A-Frame: This style has extra space along the sidewalls, which allowed for better air circulation (DeFacio et al. 2000). The steep ceilings and inability to adapt this type to a gutter-connected system leave it better suited for smaller, low to mid-tech greenhouses on ground level.

Semi-Solar (Skillion): Similar to the lean-to except that the back wall is not a solid mass, the skillion or semi-solar greenhouse experiences poor light transmittance due to reflection at low sun angles (Badgery-Parker 1999), although this can be mitigated some by increasing the height of the back wall to create a steeper roof slope (Taki et al. 2016).

Sawtooth: Sawtooth roofs exist as both curved and flat typologies. The flat sawtooth is a semi-solar, gutter-connected design, thus a southern orientation is essential for performance, as is true of solar greenhouses in general (Proksch 2017).

Roof Type	Sources
Hoop (Tunnel)	(Proksch 2017, Badgery-Parker 1999)
Quonset	(Taki et al. 2016, Proksch 2017, DeFacio et al. 2000, Dalai et al. 2020, Nelson 2014)
Dome (Arch)	(Taki et al. 2016, Badgery-Parker 1999)
Gothic	(DeFacio et al. 2000, Nelson 2014, Dalai et al. 2020
Flat Arch	(Badgery-Parker 1999)
Solar (Chinese)	(Proksch 2017)
Sawtooth	(Dalai et al. 2020, Goldammer 2019)
Geodesic	(Geodesic Dome n.d., Perez 2017, 3DIR Greenhouse Dome n.d.)
Hydraulic (Granpa)	(Nelson 2014, Granpa Hydroponics Dome n.d., Fang et al. 2007)

Fig. 2.6: Curved Roof Typologies

Curved Roof Types

Hoop/Tunnel: While not widely used in controlled environment agriculture, the hoop or tunnel type represents one of the simplest greenhouse typologies, making it a popular choice for low-tech commercial operations as it offers easy construction at a minimal cost (Proksch 2017). Due to a lack of vertical walls, this type suffers from poor ventilation (Dalai et al. 2020).

Quonset: The Quonset typology is a slightly modified version of the basic tunnel, consisting of a similar arched roof, only raised up on low sidewalls to improve clearance and allow for additional ventilation (Goldammer 2019). The presence of raised walls also allows this type to become gutter-connected (Dalai et al. 2020), with the edges of each arch connected by gutters and the sidewalls removed except for the outermost barrier.

Dome: Similar to the Quonset, except for the arch is radiused, and forms a half-circle, while the Quonset has a higher ridge with a more parabolic shape (Taki et al. 2016).

Flat Arch: A low arch sits on raised walls, improving interior space while utilizing a relatively simple structural system (Badgery-Parker 1999) of bent pipes instead of the truss assembly required for a gabled roof of the same span.

Gothic: The high gothic arch is better suited for growing ornamentals and flowering plants rather than for agricultural use (DeFacio et al. 2000). The steep slope allows for efficient and uniform light transmission, along with decreased interior condensation (Goldammer 2019).

Solar (Chinese): The solar or Chinese greenhouse is an innovative style utilizing a curved roof attached to an upright massing wall on one side (Proksch 2017). Because the roof shape is designed to receive as much solar radiation as possible, this typology is largely implemented in south-facing orientations in cooler climates that benefit from passive solar heating [cite].

Sawtooth: The arched sawtooth roof offers the same ventilation benefits as the flat sawtooth type, with a ridge vent running the length of the greenhouse at the space between the two arch intersections (Dalai et al. 2020). The arch shape offers excellent light transmission (Dalai et al. 2020), which paired with the integrated ventilation, makes this a strong choice for a passive, semi-enclosed greenhouse.

Geodesic: The geodesic greenhouse dome is not typically seen in commercial applications due to the limited interior space. Due to the circular dome shape, the greenhouse offers excellent ventilation and light transmittance for its size, making it popular for non-commercial uses (3DIR Greenhouse Dome, n.d.). The geodesic dome also performs well in a small footprint, making it a common choice for research where the ability to create multiple different controlled environments with minimal resources is highly valuable (Perez 2017).

Hydraulic (Granpa): Hydraulic or air-supported greenhouses have been around as early as 1969, and though they offered an attractive span-to-cost ratio, never caught on due to fears of structural failure compared to fixed frame types (Nelson 2014). Through innovative manufacturing and design strategies (Granpa Hydroponics Dome, n.d.) and growing research interest, largely due to its simple and effective structure and envelope integration (Fang et al. 2007).

2.4 Structure & Envelope

As greenhouses are structures optimized for growing plants via solar energy, the shape and angle of the roof is the most important design factor when evaluating a new structure. Since the roof shape itself is integral to this, and because wind loads represent one of the most significant external factors on a greenhouse (Jiang et al. 2020), the structural system and arrangement become equality important from a design standpoint. In regards to structural engineering, greenhouses are light frame structures typically made of steel or aluminum with a lightweight cladding system attached directly to the underlying structural framework (Maraveas 2020).

Since the central design objective of all greenhouses is obtaining the desired light transmittance, the configuration and assembly of the structure can have significant impact on a number of additional performance aspects, including ventilation for controlling interior temperatures, shading caused by truss and roof member positioning, and the ability to transfer wind and other loads effectively to the ground or host building (Maraveas 2020).

Typical Assemblies

Greenhouses are typically assembled from a kit of parts catalog, although given the diversity of greenhouse designs and applications, the elements of these kits are typically unique to the specific manufacturers, which tend to develop and build their product lines as a highly vernacular and contained system (Navnath et al. 2020). As a formal system, the greenhouse itself is modular, with a relatively simple hierarchy which is immediately expressed due to the lack of interior assemblies. A typical structural arrangement is as follows:

Squared or Tubular steel columns are anchored to a concrete slab (on grade or the roof of the host building) via steel plates welded to the base of each column (Proksch 2017). These columns support the roof trusses, the shape of which are determined by the roof typology, the span requirements for the growing space below, and the structural loads. These trusses carry both the exterior cladding system, as well as transfer the wind and other loads directly from the roof, through the columns, and down to the ground.

This combination of base plate, column, and roof truss forms the basic component of the greenhouse: a portal frame. These frames are typically arranged linearly, and in the case of gutter-connected designs, placed side by side as well. Portal frames typically alternate between structural and non structural, where the structural version transfer loads to the ground via columns and the non-structural frames, identical in appearance except for the lack of columns, transfer their loads to the nearest structural frame (Fernández-García et al. 2020).

A series of secondary, axillary structural members provides additional rigidity between these alternating portal frames in such a way that for most greenhouses, regardless of size or type, the basic structural system can be reduced to the repetition of this single frame portal (Fernández-García et al. 2020).

Structural Variants

While this represents the typical structural assembly of most greenhouse designs, it is by no means a rule. As mentioned previously, greenhouses by nature are largely a response to the surrounding climate and environmental constraints, making the range of expression found in their structural systems as equally diverse. Tensioned structures, such as those prevalent in the Almeria region of Spain, use a series of steel cables spanning wood columns to support a lightweight plastic film covering (Peña et al. 2020). While the basis of this design is, from a materials perspective not much more advanced than a basic hoop house made of bent galvanized steel pipe and plastic sheeting, the skill required to build and assemble a tensioned structure is significantly higher [cite], and researchers have started considering how the idea of a lightweight tensioned structural system with a membrane covering might be applied to a high-tech, closed environment greenhouse design (Muñoz-Liesa et al. 2020).

Loads

There are four primary categories of load forces which a greenhouse structure must carry, and these vary depending on climate and agricultural operation type.

Wind Loads: The greatest forces are wind loads, which must also be balanced with the need for constant ventilation through the space, creating suction forces that also need to be anticipated. Regarding wind loads in general, gutter-connected and multi-span greenhouses that are three bays or wider have greater wind resistance than those which are less than three bays wide (Fernández-García et al. 2020).

Permanent Loads: Also know as dead loads, these represent the self-weight of the structural frame, axillary and climate control systems suspended on those frames, and the weight of the covering system.
Crop Load: The crop load replaces a typical live load in a building, since there are not usually people or additional interior floors of a greenhouse. However, the crop load represents a fluctuating force in greenhouses where the growing system is suspended from the overhead truss assemblies (Fernández-García et al. 2020), such as greenhouses where tomatoes or cucumbers are growing as hanging vines.

Snow Load: While not applicable to low-tech greenhouses in Mediterranean or tropical climates, the snow load represents not only an important factor in design, but material. The greenhouse must be able to withstand significant weight, hence the use of more robust structural assemblies in colder climates, such as the Venlo style [cite]

Material

Like the underlying structure, the choice of covering has an equally important role in greenhouse design. Both the material and system are directly related to the performance of a number of conditions, including optimal light transmittance, underlying structural assembly, geographical location, static and dynamic loads, as well as intrinsic internal factors such as volume, floor area, and height (Shamshiri et al. 2018). Because of the significance of coverings as a factor of greenhouse performance, there is a large body of academic research on related topics, including the integration of photovoltaics (Zisis et al. 2019, Zhang et al. 2021, Minanda et al. 2021), adaptive facade systems (Rufí-Salís et al. 2020, Muñoz-Liesa et al. 2020, Firfiris et al. 2020), and harnessing kinetic energy to convert for use inside the greenhouse (Jiang et al. 2020).

Material choice for the greenhouse covering is largely dependent on if the greenhouse is passively ventilated with input from the surrounding environment. or if the growing space is closed and thus sealed off from the outside. Passively ventilated greenhouses typically fall into the low to mid-tech range, and use a plastic sheeting or panel system to cover the structural frame, increase the interior temperature, and provide shading when necessary in mid-winter or warm regions (Villagrán et al. 2019). Passive greenhouses, like other passive building strategies, rely on the exterior climate to help control and regulate interior conditions though vents and openings (Villagrán et al. 2019), making them ideal for plastic as a covering material. Additionally, these are typically located where extreme snow loads are not a concern, thus alleviating the need for more robust cladding choices (DeFacio et al. 2000). Closed environment agriculture, in contrast, benefits from the enhanced rigidity, thermal properties, and longer lifespan of glass compared to plastic.

Another significant factor in material choice is related to the ability of the material itself to uniformly scatter solar radiation in a uniform matter (Cabrera et al. 2009). Intrinsic to each covering material is a set of intrinsic properties specific to that particular material, including roughness, bulk heterogeneities, and addition of other particles during the manufacturing process (Cabrera et al. 2009). The performance of the material is additionally impacted by external factors, most of which are environment specific, including condensation, dust deposits, and material breakdown due to aging (Cabrera et al. 2009).

Depending on the technology level, climate, and transmission needs of the greenhouse, there are a range of materials typically used for covering: single pane glass (2-3mm), single or double wall polycarbonate panels, fiberglass, UV stabilized polyethylene film, copolymers, and polyvinyl chloride, and selective transmission medium (Cabrera et al. 2009). There is some research around the use of Ethylene Tetra Flouro Ethylene (ETFE) as an innovate covering due to it's self-cleaning/self-healing properties, with only 1% of the weight of an equally sized piece of glass but allowing for 95% light transmission (Kalantari et al. 2017).

Adaptive Strategies

Beyond the basic material choice, a number of recent studies have looked at greenhouse coverings as an adaptive system capable of providing additional performance benefits. A bioclimatic (dual skin) facade system allows for the interior space to be automatically regulated based on exterior climactic parameters (Rufí-Salís et al. 2020) using the interstitial space between two layers of polycarbonate panels and a series of shuttered openings (Muñoz-Liesa et al. 2020). Another novel covering strategy involves the integration of triboelectric nanogenrator (TENG) yarn into the covering material, allowing the facade to harvest energy from irregular or low frequency mechanical energy in the environment such as rain drops hitting the surface (Jiang et al. 2020). The use of lightweight covering material, such as polyethylene plastic, in colder climates presents challenges due to thermal regulation. However, research involving an dual wall air-inflated greenhouse that pumps mist into the wall cavity when temperatures drop below freezing, creating a temporary barrier of ice that acts as insulation while still allowing for light transmittance during colder months (Firfiris et al. 2020).

Photovoltaics

There are a number of recent studies on the integration of photovoltaics (PV) into greenhouse coverings, suggesting a development in greenhouse design that revisits what were once discrete factors as new opportunities for deeper systems integration and performance, such as offsetting the energy consumed from system controls without any negative impact to plant production (Zhang et al. 2021). Silicon-based PV cells are (rigid), making them idea for integration into glass coverings with the added benefit they offer the highest performance in regards to available PV technology (Zisis et al. 2019). Other PV technologies are offer some physical flexibility for shaping to curved roof types; however, they are not as efficient and many greenhouses with curved roof shapes are made of PE film or similar plastic sheeting, preventing them from supporting the weight of the PV cells have prevented broader adoption (Zisis et al. 2019). PV cells can also double as shading devices (Proksch 2017), adding another level of value to an integrated greenhouse design system.

2.5 Lighting

Greenhouse are, by definition, spaces built for performance, and primary to their function for plant growth are a number of systems that regulate and maximize light, the central resource necessary for photosynthesis.

Natural Lighting

Greenhouses are environments optimized for plant growth, which means the application, control, and distribution of lighting necessary for photosynthesis is a significant factor in design, especially in regards to solar radiation (Nadal et al. 2017). Greenhouse coverings, ranging from semi-opaque to fully transparent, diffuse this solar radiation into the interior growing spaces. In order to control the light levels, a variety of methods are used to manage both light condition and temperature including plant density, shading screens, and artificial lighting (Shamshiri et al. 2018).

At the most basic level, the light requirements for plants are grouped into low intensity (500-1250 foot-candles), medium intensity (1250-2500 foot-candles), and high intensity (+2500) ranges (DeFacio et al. 2000). However, this is a rudimentary form of measurement, especially since foot-candles are a photometric unit measuring the amount of light visible to the human eye (Torres et al., n.d.). A more specific measurement of available light comes in the form of photosynthetically active radiation (PAR), which occurs in wavelengths between 400 to 700 nanometers. While still withing the wavelength of light visible to the human eye, PAR is limited specifically to the range which increases plant photosynthesis (Torres et al., n.d.).

Appropriate light intensity is important, as excess light does not result in increased plant growth, but can increase heat inside a greenhouse, or in the case of artificial lighting, increase energy costs with no additional return on value (Torres et al., n.d.). In order to asses this, another form of measurement, daily light integral (DLI) is used, which measures the amount of daily PAR as a function of intensity, with the results being cumulative to the total number of light photons accumulated on a given spare meter on a given day (Torres et al., n.d.).

In order to optimize a greenhouse for solar incidence and improve light transmittance, the orientation of the greenhouse structure is a significant part of the design process. A greenhouse is typically oriented so that the long axis runs east to west for locations above 40 degrees latitude, and for locations south of 40 degrees latitude, the long axis is rotated north to south to take advantage of passive ventilation during hotter months and reduce the amount of shading (United States Botanic Garden, n.d.).

Another advantage of a north-to-south orientation is a constantly changing shadow pattern inside the greenhouse as the sun moves across the sky, resulting in dynamic shading which improves light distribution compared to a fixed pattern (Goldammer 2019). For the exterior facade, recommended minimum solar radiation requirements for greenhouses are in the range of 1900–2000 MJ/m2 per year, or 13–14 MJ/m2 per day for ideal production (Nadal et al. 2017).

Supplemental Lighting

Depending on the amount of solar incidence reaching the inside of a greenhouse, supplemental electric lighting may be necessary for consistent plant growth (Kozai et al. 2016, Proksch 2017). There are a wide range of extrinsic variables impacting how much ambient light is transmitted into the greenhouse, including geographical location (Proksch 2017), dust & condensation, intrinsic diffusive properties of the covering material, and material aging (Cabrera et al. 2009). Typical lighting sources include incandescent (halogen) lamps, discharge lamps (including fluorescent, metal halide, and high-pressure sodium), and light-emitting diode (LED) lamps (Shamshiri et al. 2018, Goldammer 2019). LED lamps are the most common, offering a wide range of benefits over other types of lighting including low thermal energy output, compact design, efficiency, and cost (Shamshiri et al. 2018).

While electric lighting is common in greenhouses located in northern latitudes, as the low light intensity in winter months requires supplementation to sustain year-round growth (Proksch 2017), more greenhouses are including electric lighting in controlled environment agriculture. These greenhouses are sometimes referred to as controlled environment plant production systems (CEPPS) (Kozai et al. 2016), since the addition of electric lighting into a controlled environment allows for fine-tuning and systematic control of growing variables at a high level. In controlled environment agriculture, supplemental lighting has become increasingly common in order to mitigate the risk of days with low light incidence, which could slow the carefully scheduled plant cycles in a fully automated greenhouse (Kozai et al. 2016).

2.6 Heating, Cooling, & Ventilation

Greenhouses are simple structures in concept, but represent a collection of complex and integrated systems. There are a number of important climatic parameters which must be managed inside a greenhouse to maintain the optimal growing environment, including solar radiation, carbon dioxide, thermal regulation, and airflow (Taki 2016). The regulation of heating and cooling represent one of the greatest energy investments in both the design and operation of a greenhouse (Firfiris 2020), while cooling representing a higher cost to purchase over heating (Ruijs 2020). Because of this, temperature is typically regulated thought heating, natural ventilation, and energy conservation (Choi 2019).

Heating

Due to the significant operational costs associated with heating and cooling, there is a trend in greenhouse design to seek passive strategies such as solar orientation, solar massing walls, and insulated panels in non-glazed areas (Ceres NetZero Greenhouses, n.d., Muñoz-Liesa 2020). Since commercial greenhouses are designed to prioritize efficiency, which helps keep operational costs down, passive design strategies can reduce the energy requirements by as much as 30%, depending on the climate (Muñoz-Liesa 2020).

Greenhouse cultivation occurs year round, which means a heating system, even in warmer climates, is necessary to keep the interior temperature at a consistent level (Firfiris 2020). Heat loss primarily occurs during the night in winter months (Proksch 2017), since the same materials which tend to allow for high light transmittance also offer poor insulative properties. Sources of heat include a range of sources, from fossil fuels, alternative heating, biomass, and waste heat recovered from integrated buildings (Proksch 2017).

Heating system installation typically represents 30-60% of the total investment costs in a greenhouse, while the operation costs are between 65-85% of total production costs, depending on the climate (Firfiris 2020). Temperature drops are most significant in colder climates as they can result in frost damage if left unchecked, however even Mediterranean and sub-tropic regions experience enough of a shift in winter months to warrant the inclusion of some form of heating system (Firfiris 2020). The use of passive solar strategies to can eliminate the need for additional heating almost entirely (Prosch 2017).

One challenge for many low to medium tech greenhouses which use an air-inflated skin is the poor thermal retention in the sheeting material used for covering, which can often result in crop frost during winter months in moderate climates (Firfiris 2020). There is some literature looking at how spraying a mist of water between two layers of plastic sheeting as temperatures drop create a temporary layer of ice, insulating the interior space until the exterior warms enough for it to melt (Firfiris 2020).

Cooling

Due to the high operational cost of cooling systems, strategies such as natural or forced ventilation and shading systems are typically implemented first (Prosch 2017, DeFacio 2002). If temperature regulation cannot be achieved using these methods, then evaporative cooling systems will often be added, in which air from the outside is pulled into the greenhouse through porous screens saturated with moisture (Prosch 2017), or mist is produced from a nozzle system while forced air is passed through the growing space (DeFacio 2002).

Evaporative cooling has an additional benefit of increasing interior humidity, but the trade off is that the exterior air must be relatively low humidity, and in closed environment growing operations, the air entering is not filtered or conditioned (Prosch 2017). Mechanical air conditioning systems are not typically used due to high operational costs and poor efficiency, (DeFacio 2002), although there are rare instances where they are still used (Prosch 2017). A novel system type, the ground air heating system (Ceres NetZero Greenhouses, n.d.) consist of an air chamber under the greenhouse floor. The air is cooled as it passes across the soil before being recirculated back into the greenhouse.

Humidity

Relative humidity inside a greenhouse is indirectly related to the temperature, and must be controlled like any other environmental factor to maintain a favorable environment for growing while also preventing condensation from forming, which increases the risk of fungus, pathrognes, and disease (DeFacio 2002). Most greenhouses require a relative humidity between 45-85% depending on the crop, but anything over 85% will typically lead to condensate (DeFacio 2002).

Thermal/Shading Screens

Shading screens are made of woven material deployed across the ceiling spans inside greenhouse, and are used to shade areas from solar radiation during the day (USBG, n.d.. Kotilainen et al. 2018) and conserve energy costs by preventing heat loss at night by acting as a thermal blanket (Kotilainen et al. 2018, Prosch 2017, Taki et al. 2016). The screens, also referred to as thermal screens, movable curtains, and heat blankets (Prosch 2017) are typically made of a semi-porous material which allows collected moisture to evaporate during the day. When used at night as a thermal barrier, they can reduce fossil fuel consumption required for heating by up to 50% (Taki et al. 2016).

Passive Ventilation

Greenhouses require ventilation to bring fresh air into the growing space, regulate temperature and relative humidity, and replenish carbon dioxide necessary for plant growth (DeFacio 2002). However, ventilation is only effective for controlling temperature and humidity when the values outside are lower that what is inside the greenhouse (Shamshiri et al. 2018), which can create problems with insufficient CO2 in climates or conditions where this is not the case.

A naturally ventilated greenhouse requires consideration of the structure, insulation, ceiling slope and ventilation openings on the roof (Shamshiri et al. 2018) in order to operate efficiently. Ventilation is handled via a combination of ridge vents along the roof and side vents along the walls: warm air rises to the top, escaping at the ridge while cooler air enters into the greenhouse from the lower side vents (Prosch 2017). Wind can improve this process if the ridge of the greenhouse is oriented perpendicular to the direction of prevailing summer winds, generating a vacuum on the leeward side of the ridge (Prosch 2017).

Passively ventilated greenhouse must also take into account nearby objects, which can block airflow and cause negative impacts to the thermal performance (Villagrán 2019), which can be further compounded in areas with low wind velocity. This can addressed by increasing the ridge vents via modeling to properly upsize the ridge vents, compensating for vertical obstructions around the walls (Villagrán 2019).

Mechanical Ventilation

Electric fans located on end walls are used to increase ventilation and help cool down interior temperatures. These fans are typically horizontal airflow fans (HAF), sized to exchange the entire volume of air inside at a given rate, and in addition to airflow, help distribute heat and reduce condensation on plants (USBG 2019). Vents may be operated manually, or more commonly in the case of automated greenhouses, are operated by a shutter motor which opens and closes the vents to maintain the appropriate microclimate inside (Minanda et al. 2021).

Mechanical ventilation is also necessary for fully closed environment greenhouses, which continue to increase in popularity (Teitel et al. 2012). A closed greenhouse is completely sealed from the outside environment, which allows it to conserve energy and water, reduce pesticide use, and increase CO2 levels (Teitel et al. 2012). For greenhouses which are not entirely sealed off, passive ventilation is still an option; for CEA greenhouses, any air entering the growing space needs to be conditioned and filtered first. Despite this requirement, closed greenhouses are continuing to dominate the commercial greenhouse industry due to the high (approximately 20% of production) costs required heating and cooling a conventional greenhouse (Tietel et al. 2012).

2.7 Irrigation & Climate Control Systems

Irrigation

Greenhouse irrigation systems are highly dependent on the type of plants grown inside, however as a general design guideline a typical greenhouse requires two quarts per day per square foot at peak use (DeFacio 2002). Irrigation systems fall into three types: overheard, surface, and subsurface. Overhead systems spray water directly onto bedded plants, exposing the foliage to water, while surface systems spray water beneath the foliage but on top of the growing medium, and subsurface systems, including hydroponics systems, water only the roots (DeFacio 2002).

High wire irrigation systems, widely used in Venlo style greenhouse that originated in the Netherlands, uses drip irrigation which filters into rockwool slabs set in gutters suspended along a vertical wire, which prevents foliage and fruit from coming into contact with the nutrient solutions and allows for reuse of process water (Ruijs 2020). A rainwater harvesting system (RWHS) can offset the water usage of a greenhouse by capturing water runoff from the roof and storing it for later use. These systems function in three basic configurations (Parada et al. 2021):

Open Management (OM) System: traditional greenhouse irrigation where excess supply is drained and discharged to a lecahte pool or wastewater sewer.

Recirculated Control (RC) System: irrigation system where the drained water us collected and recirculated back into the hydroponics system.

Recirculated Reduction (RR) System: an advanced method in which the excess supply is used to calibrate a reducing in total irrigation, so that the excess runoff is reduced even further before being collected and recycled back into the system, cutting down on evaporation that might occur during the entire process.

Climate Controllers

Climate control systems are either based on open-source/open-hardware standards, or they are closed systems with precise capability for a specific plant growing condition (Ferrer et al. 2019). Modern greenhouses function as closed ecosystems, especially in the case of closed environment agriculture, and thus require manipulation of passive and active ventilation, evaporative cooling, shadings, refrigeration, heating, and dehumidification (Shamshiri et al. 2018).

These controllers also have the ability to reduce labor costs, which can account for up to 50% of total operating costs, while simultaneously improving crop quality and yields (Engler et al. 2021). A microclimate controller is responsible for monitoring a wireless sensor network (WSN), which transmits data from sensor nodes to provide early real time climate monitoring, warning messages, and remote control of mechanical systems (Shamshiri et al. 2018).

Climate control programs operate between the boundaries of Optimal Control (OC) and Soft Computing (SC): OC applies quantitative analysis to achieve optimal performance in regards to a specified set of variables, typically speed, cost, etc., while SC moves in the opposite direction by utilizing qualitative analysis and symbolic knowledge representation such as linguistic or graphical data (Balas et al. 2018).

Expert control, one of most commonly found SC techniques in controlled environment agriculture, focuses on parameters such as stability, adaptation, and robustness, given that both humans and plants are tolerant to a range of quantitative parameters such as temperature, humidity, and air composition, and thus can sacrifice accuracy for larger goals (Balas et al. 2018).

2.8 Key Concepts

The results of this review indicate that while there is already a significant body of research on greenhouses ranging from performance optimization and innovation to policy and urban-specific issues, including zoning issues (Sanyé-Mengual et al. 2016), there is very little research examining greenhouses from an architectural perspective.

This represents an opportunity for investigation, especially as such a need has not gone unnoticed, with published works citing a lack of information on topics specific to the built environment, including the potential for sharing of metabolic flows between a greenhouse and a host building (Sanyé-Mengual et al. 2016), the aesthetic value of agriculture in the urban environment (Ling et al. 2018), and intrinsic understanding regarding the use of thermal mass, shading, and passive heating and cooling systems with greenhouse designs (Engler et al. 2021).

The role of this literature review is to establish a consistent understanding of the greenhouse from the perspective of the built environment, providing a resource for future research specific to addressing these and other building-integrated needs.

III. Methodology

Greenhouses & the Built Environment

Methodology

Chapter 3: Methodology

3.1 Research Methods

The research design for this project begins with an in-depth literature review of greenhouses. Review materials included topics relevant to any form of greenhouse in any capacity, which included experimental designs. Due to the applied nature of the design framework, in addition to peer-reviewed journal articles and books, review materials also included technical documentation from greenhouse manufacturers, educational manuals and training publications related to greenhouse management and operations, and when necessary, websites and multi-media resources. These sources were all analyzed and coded using a qualitative research methodology, and the resulting code book provided the bare form of what would then be expanded upon into the integrated design framework.

The design framework was organized as a theoretical workflow for applying a hierarchy of design principles related to greenhouse performance and operation into a consolidated structure. Since greenhouses are essentially performance-based buildings, climate and geographic location are the most important factors in any design. Starting with these, followed by solar access, which governs the second most important variable in greenhouses, light, a conceptual model of the related greenhouse systems was organized into the order of impact each variable had on the balance of the overall controlled environment.

A series of theoretical frameworks were developed concurrently as a result of emergent topics that arose as the framework expanded. If the literature review is the foundation of this work, then the design framework is the structure and the theoretical frameworks might be thought of as the roof: the expression of an underlying form, significant to the overall design but existing as a response to underling design decisions. Three theoretical frameworks in total were developed, centered around prioritizing the architectural design, the agricultural component, or the metabolic resource flows of the resulting building.

In the applied design portion, the resulting framework is used to select a potential site from a three unique and varied climates, then support an exploration of what a proposed design might look like by working through each section of the framework beginning with climate assessment and site placement. This section also utilizes a greenhouse simulation tool, Virtual Grower 3, as a method for developing an initial cost model for each climate, adding some concrete metrics like potential heating, cooling, and lighting costs toward the comparison of each location. Using the framework, a building concept is moved from concept through to schematic design to fully explore how the process might inform cooperative design strategies for a specific building at an actual, physical location.

3.2 Literature Review

Review Materials

In order to accurately examine both current developments, as well as best practices for greenhouse design, this review draws from a wide range of sources. Material for this review was primarily collected from academic published sources, including journals, books, & conference papers. Information

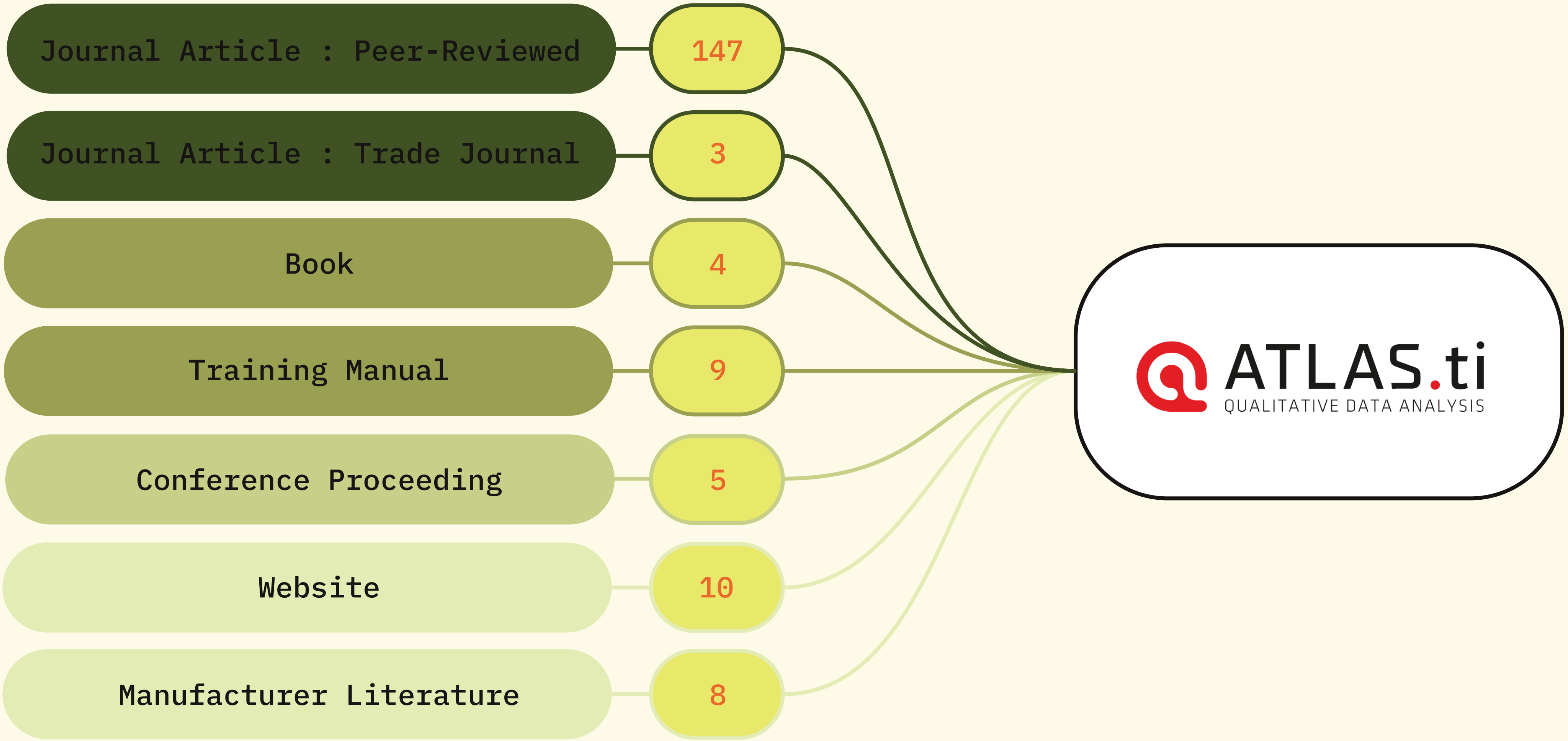


Fig. 3.1: Review Materials

from industry publications, reports, technical literature, and greenhouse manufacturer websites were used as supplemental material when no published academic literature existed for a given topic. Literature includes any research or topic related to the structure, enclosure, typology, or system of a greenhouse for both integrated and ground-based greenhouses engaged in any form of plant production.

Assessment Criteria

In order to systematically source, assess, and organize current literature, a formal process was established based on the following selection process: 1) Query, 2) Selection, 3) Content Review), 4) Supplementation.

Various academic databases were queried using a series of search terms that followed a hierarchy of specificity, beginning with the most general and moving towards keywords for specific subtopics within greenhouse design. Additionally, because of the proximity of greenhouses to the built environment, as well as their central role in building-integrated agriculture, terms specific to greenhouse & building integration were also used to cover the spectrum of greenhouse design, both as ground-based, vertical, or rooftop integrations.

Because there is precedent for
here is a wide range of variability when discussing rooftop greenhouses, since both terms may refer to both a fully integrated, enclosed and high-tech glasshouse or a simple, low-cost open high tunnel with soil as the growing medium. One of these is placed, and the other is integrated, although the same term is used to describe both regarding the general typology.

In order to avoid this confusion, for the scope of this paper two additional criteria were added for the selection of literature regarding building integration in order to narrow material in this category to the relationship between the building and the greenhouse: 1) the greenhouse must be compliant with closed environment agriculture practices, specifically that it has its own dedicated environmental control system and utilizes a soil-less growing method, and 2) the greenhouse was being used for agricultural practices.

Selection Process

Articles that generated hits with the word “greenhouse” in the title were selected from the search results, followed by an assessment of the abstract to ensure the article or material fell within the scope of this review. If a piece of literature met both of these criteria, then it was imported into a citation management system. Once a significant body of work had been collated, the material was imported into Atlas. ti, a qualitative data management system.

An initial codebook, based on the general topics of greenhouse design, was used to sort the literature by category and subtopic. Articles were read and coded using Atlas.ti, a qualitative data analysis software. This allowed literature to be codified and observe emergent trends.

Certain topics had a high number of associated references, such as structural performance or solar radiation access. Other topics were mentioned less frequently: in order to assess their validity in relation to greenhouse design, additional searches were conducted to find if other sources of literature existed beyond peer-reviewed publications.

This methodology allowed for flexibility in assessing emergent topics as the code tags accumulated within the database. At the start of the review, some terms and subtopics, such as the need for better simulation tools, were not clearly defined. These emergent topics were often mentioned in the methodology rather than as a core component of the work, so assessing the cumulative codes provided important insight not just into the explicit subjects of the review material,

I. Development

a. Terminology
b. Closed vs Open Design
c. Freestanding vs Gutter-Connected

II. Typologies

a. Roof Type
b. Technological Investment
c. Ground Condition

III. Structure & Envelope

a. Structural Assembly
b. Load Considerations
c. Covering Material

IV. Internal Systems

a. Lighting
b. Ventilation
c. Heating & Cooling
d. Irrigation
e. Climate Control

V. Design Factors

a. Operations
b. Climate
c. Impact

VI. Integration

a. Host Considerations
b. Subtypes
b. Circular Systems
c. Program

Fig. 3.2: Conceptual Framework

but the processes and systems through which these projects unfolded, providing valuable insight into the creation of a system which integrates these into a single, coherent framework.

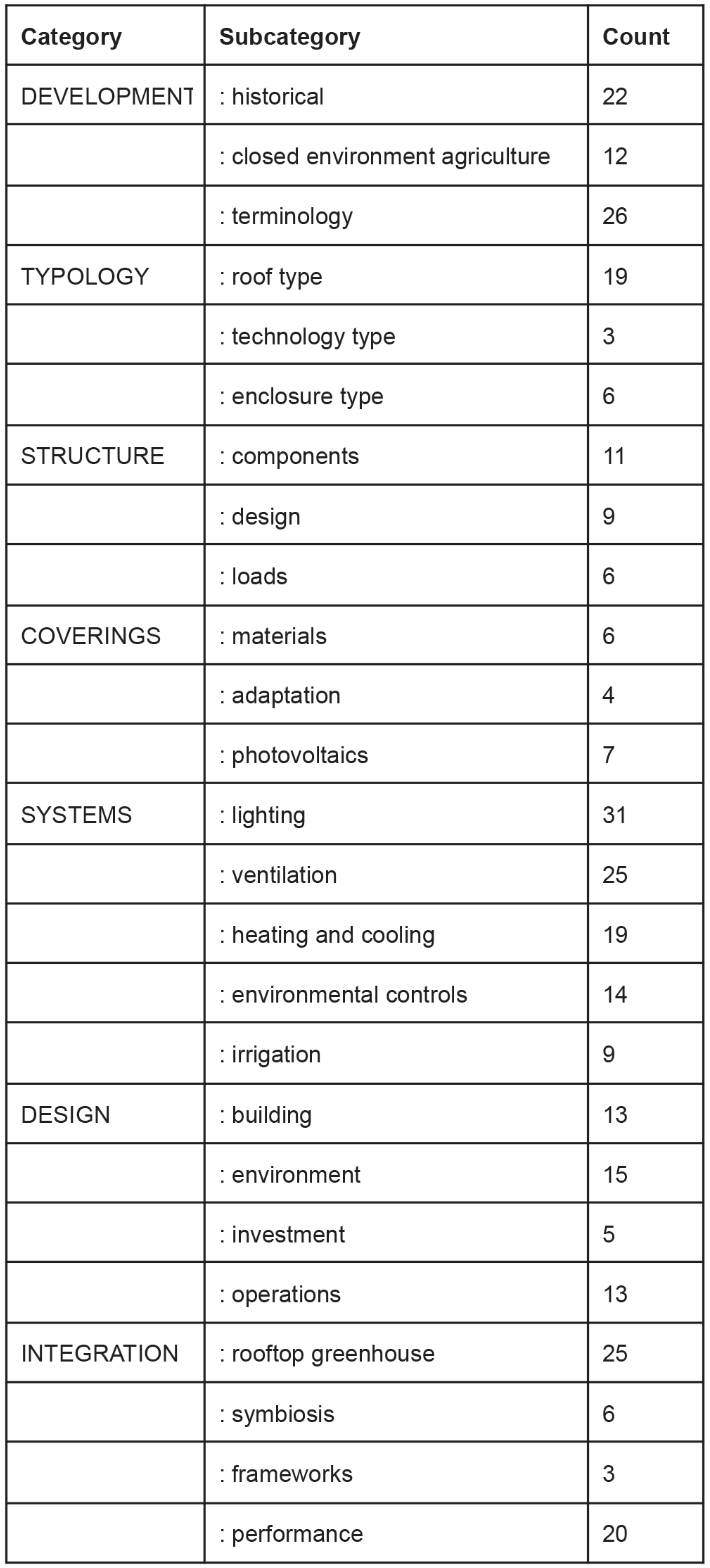
Conducting a literature review as a meta-analysis of both the topics of research but also the processes by which greenhouses are systematically assessed provided valuable insight into the needs around a systematic framework for analysis, a process which is reflected in the development of this project as well.

3.3 Design Framework

A conceptual framework for greenhouse organization was constructed based on the categories which emerged from the literature review. This outline was based on categories of research around greenhouses and served as the guideline for design framework that resulted by dividing discreet greenhouse systems, considerations, and typologies into six categories:

Development: This section includes terminology, conditions (open vs. closed), placement (ground-based vs rooftop), and arrangement (freestanding vs. gutter-connected). It serves at a high-level design choice which dictates the relationship of the greenhouse to the host building, the main solar orientation, and the bay arrangement and enclosure conditions.

Typology: Once the primary massing is established, typology informs the form that massing begins to take. By selecting and prioritizing one of three primary modes of greenhouse classification: roof type, technology type, and organization type. A greenhouse may often encompass multiple typologies, since these categories include both roof shape, programmatic function, and environmental control strategy. By examining all the current typologies, an informed decision about which forms to select that best support the overall design goal will help refine the design into more specific



Category	Subcategory	Count
DEVELOPMENT	: historical	22
	: closed environment agriculture	12
	: terminology	26
TYPOLOGY	: roof type	19
	: technology type	3
	: enclosure type	6
STRUCTURE	: components	11
	: design	9
	: loads	6
COVERINGS	: materials	6
	: adaptation	4
	: photovoltaics	7
SYSTEMS	: lighting	31
	: ventilation	25
	: heating and cooling	19
	: environmental controls	14
	: irrigation	9
DESIGN	: building	13
	: environment	15
	: investment	5
	: operations	13
INTEGRATION	: rooftop greenhouse	25
	: symbiosis	6
	: frameworks	3
	: performance	20

Fig. 3.3 : Code Book

	Greenhouse Specific	Open Access	Daylight	Thermal	Ventilation	Loads
USDA Virtual Grower	X	X	X	X	X	
CASTA Hortivation	X		X	X	X	X
HortiEnergy	X		X	X	X	
Ladybug Tools for Grasshopper		X	X	X	X	
Solidworks CFD					X	X
WUR Adaptive Greenhouse Design Tool	X		X	X	X	
Solar Innovations Design Tool	X	X	X	X		
TRNLizard for Grasshopper	X	X	X	X	X	

Fig. 3.4: Simulation Tools

phases.
Structure & Envelope: While greenhouses are relatively simple structures in concept, the choice of material and structural configuration has a profound impact on building performance. This stage takes the typology selected in the previous category and further refines it, examining the impact of material and establishing the enclosure system though specific geometry.

Internal Systems: With the envelope now established, choices about the numerous mechanical and environmental control systems that regulate the interior microclimate of the greenhouse become important to determining the overall function. These include lighting, ventilation, irrigation, heating and cooling, humidity, and CO2, and are largely determined by the availability of natural light and ventilation, which are themselves results of the earlier design choices.

Design Factors: These factors represent a list of variables external to the greenhouse, yet play a significant role in overall performance. Considerations include operational needs and spatial arrangement of the growing areas, resilience to climate variability, and large-scale changes over time, and impact to the surrounding area including economic, social, and metabolic contributions.

Integration: With the core design parameters established, factors unique to a building integration such as shared spaces circular resource flows may be fully developed.

Once these factors were defined, then they were expanded into a more comprehensive framework with guidelines and specific parameters for each step. These steps are described in depth in chapter four.

3.4 Applied Design

In order to test the design framework, a series of three sites representing three unique climates in the Northern Hemisphere were selected. Greenhouse simulation and modeling was a significant topic that emerged over the course of the literature review. To help make an informed decision regarding the impact of climate, a base simulation was first setup and run. Results from provided estimated costs for heating and electric lighting. From this data, one site, Tucson, was selected to further apply the design framework toward a site-specific building design.

Greenhouse Simulation

There is a significant amount of research based around modeling and simulating various aspects of greenhouse design. There are already numerous tools for assessing simulation-based environmental metrics such as solar radiation, water, and energy specific models (Khan et al. 2018), such as HVAC impact on crop loads (Talbot et al. 2020). As greenhouse designs evolve, these discrete tools are being integrated into more cohesive packages, largely due to the needs of building integrated agriculture, which requires more specific parameters for optimization with a host building, often in different coupled configurations (Jans-Singh et al. 2021).

Despite these advancements, there is still limited research and information available for designers and planners in regards to the relationship between agriculture and architecture, and some literature has proposed a dedicated building integrated agriculture information modeling tool (Khan et al. 2017), which would extend the concept of building information modeling applications such as Revit to include agricultural elements. Greenhouses are performance-driven structures, allowing them to benefit from simulation and testing early in the design phase. There are a number of tools available for running simulations: some are only available in limited capac-

BASE_SIMULATION_PARAMETERS :

Multi-Span Venlo RTG
24' Span, 2 Peak, 5 Bays Total
185' x 120'
22,200 SF Footprint

Side Height: 16'
Roof Height: 21'

Double Layer Glass on Roof
Single Layer Glass for Side/End Walls

Mobile Air Energy Curtain,
Excellent Fit/Quality

Outside Air Exchange Rate: 1.25

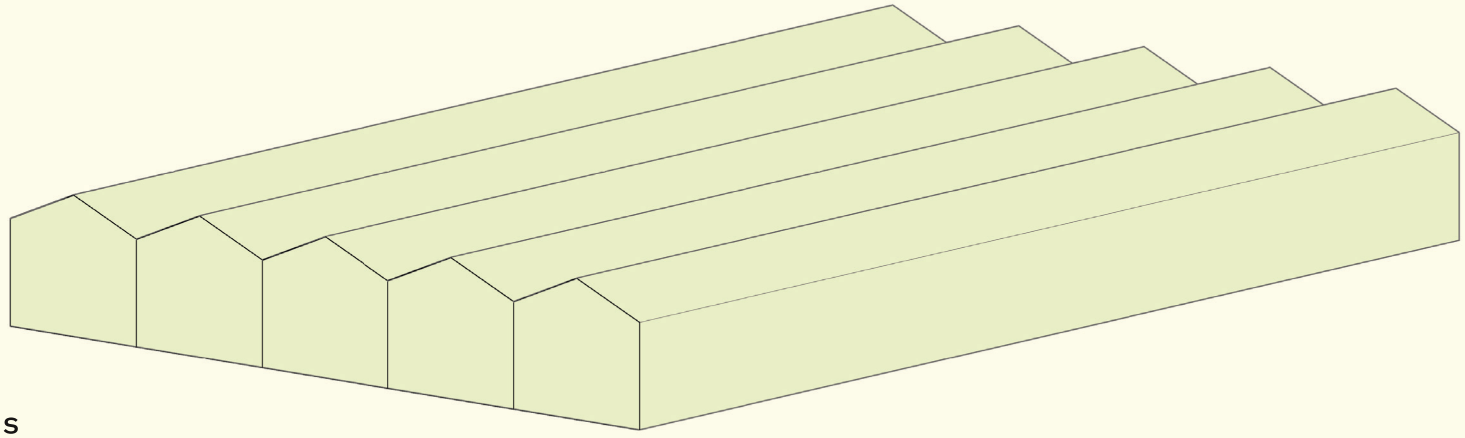


Fig. 3.5: Base Simulation Model

ity to specific greenhouse fabricators, while others are free and accessible for anyone to test and apply to a proposed design. Within the built environment, the prevalence of fully integrated rooftop greenhouse represents a new set of tools required for the designer to test initial design assumptions against desired performance outcomes.

All the simulation tools mentioned over the course of the literature review were compiled and then compared against the primary simulated conditions, which were found to be daylight, heating, cooling, ventilation, and loads. Two additional factors were also considered: was the tool specific to greenhouse design, and was it accessible to built environment professionals. For the scope of this project, USDA Virtual Grower was selected to provide preliminary cost modeling in order to aid in site selection, since the ability to predict heating, cooling, and lighting costs across a range of climates would allow for a baseline assessment for the fitness of a given location to a proposed greenhouse design. Using the Virtual Grower 3 software application, published by the US Department of Agriculture, was used to run three basic simulations for modeling cost of operation in a greenhouse in each of the climates: Chicago, IL, Seattle, WA, and Tucson, AZ.

Base Simulation Model

A venlo-style roof in a freestanding configuration was selected as a balance between low- and high-tech typologies for the cost simulation. By simulating a ground-based, freestanding greenhouse, external variables are limited to climate and weather and allow for greater control over parsing the final results. The parameters for the base model were a total area of 22,200 sf, with a footprint of 185’ x 200’. The sidewall height was 16’, and the ridge height was 21’. The roof was double layer glazing, and the sides and end walls were single layer. The air exchange rate was 1.25. These parameters represent the scope of modeling capacity for Virtual Grower 3 and are in no way the only factors to consider.

3.5 Theoretical Frameworks

In order to demonstrate how different goals might inform the application of the design framework to a building project, three theoretical frameworks were developed alongside the design matrix. These frameworks are a collection of concepts, organized around one of three core topics for greenhouse integration: architectural design, agricultural integration, or metabolic flow. They serve not as rules, but different ways of considering and prioritizing the design decisions brought on as the design framework is applied. They serve as a reminder that integrating a complex system into a building, new or existing, is not an east task. Even if the numerous technical and performance hurdles are adequately addressed during the design process, there are other considerations to be had given the larger relationship between agriculture, labor, and social expectations towards farming in urban settings, which have been found to represent a significant psychological barriers (Specht, 2017) toward greenhouse adoption. In The Unsettling of America: Culture and Agriculture, environmentalist Wendell Berry addresses this separation of urban and rural at perhaps an even greater scale, writing:

> “When the concept of country, homeland, dwelling place becomes simplified as “the environment” - that is, what surrounds us, we have already made a profound division between it and ourselves. We have given up the understanding - dropped it out of our language and so out of our thought - that we and our country create one another, depend on one another, are literally part of one another… and so cannot possibly flourish alone” (Berry, 1977).

In order to observe how greenhouses might successfully be integrated into the urban built environment, we also need to consider the extents of that environment, and were the boundaries fall. By shifting this question from one of duality

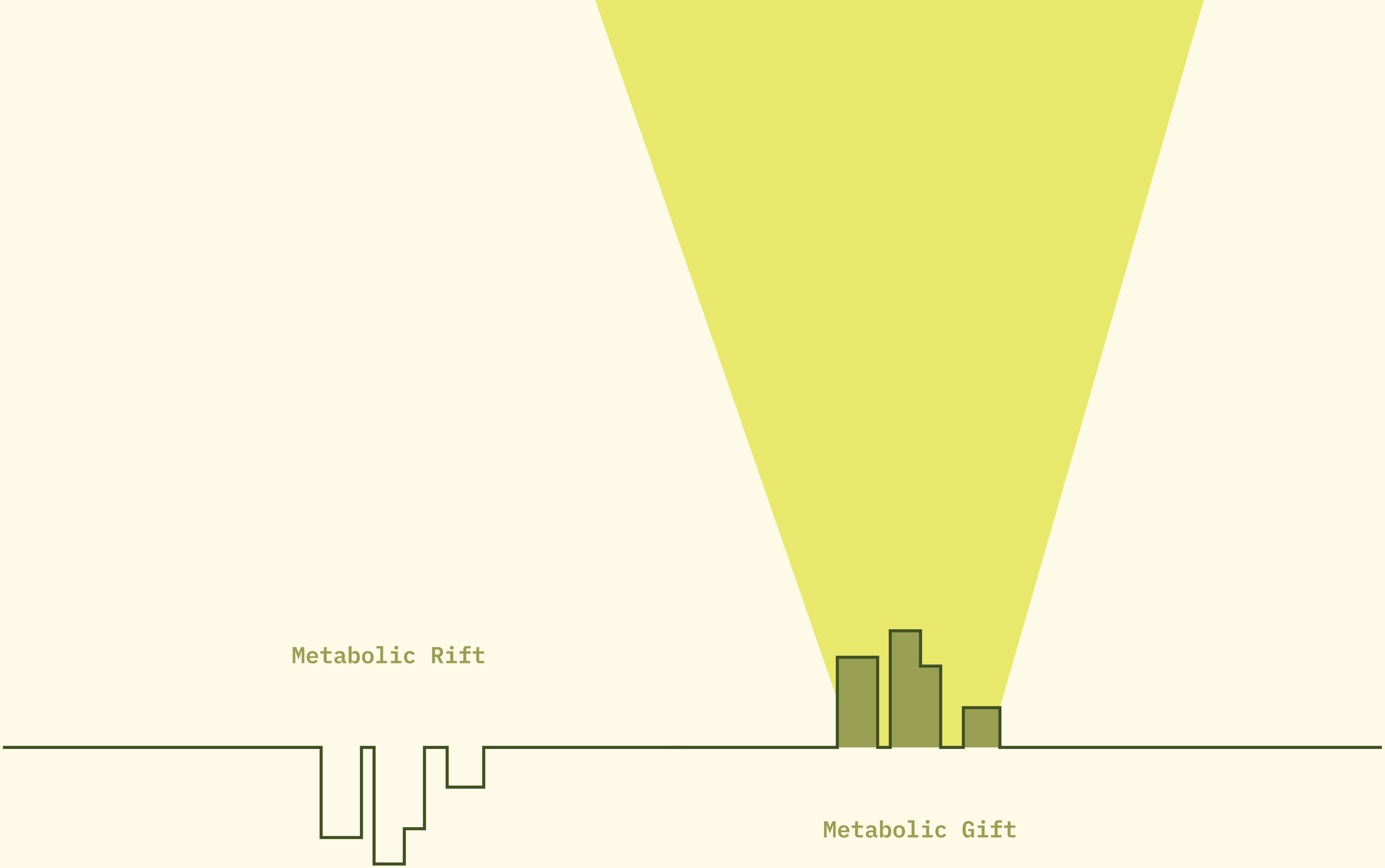


Fig. 3.6: Closing the Gap

(urban vs rural) into a concept of a blended environment, we may begin to see buildings emerge not as objects which are inserted into a place, but as adaptations of the surrounding systems; not only those familiar to architecture but with new modes and possibilities.

Buildings account for half of the world's energy consumption (Nadal, 2017), and the global building floor area is expected to double by 2060 (Architecture 2030). Additionally, agriculture accounts for 13-15% of the energy consumed in developed countries, with CEA being the largest consumer within agriculture (Nadal, 2017). It is estimated that for every 1% increase in atmospheric temperature, there is a corresponding 10% loss of land, and the carbon cycle will only continue to worsen. CEA represents a novel shift toward offsetting that negative cycle Despommier, 2013), but in order to be successful, it must also acknowledge the larger issues related to greenhouse adoption.

This presents an opportunity for innovation in how resources are consumed, but in regards to food, as well as the energy flows associated with food production. By looking at overlaps between the built environment and building integrated agriculture, we may begin to observe new methods of deeper decarbonization across both systems. And as in many systems, the integration of these two systems in a symbiotic model creates the potential for new, emergent properties to arise neither predictable nor directly from the properties of the individual parts (Vassallo, 2017).

Metabolism

The theory of metabolic rift offers a lens for understanding the role of urban agriculture in the built environment. Capitalism has created a cycle of metabolic "rifts and shifts" (McClintlock, 2009) which use geographic displacement of ecological crisis for the sake of short-term gains. This rift exists across three scales: ecological, social, and individual (Marx, 1981).

For the scope of this project, we will focus primarily on the ecological scale, since it relates directly to energy consumption at the level of agricultural production. However, it is important to note that both the social and individual scales are just as interconnected to agriculture and architecture, both in the form of labor in agricultural production, as well as the metabolic cycle of food consumption and waste generation on a personal scale.

The built environment serves primarily to shelter humans, and architecture only exists as a surplus to shelter (Moe, 2020). Humans are the organisms within this system that consume the products of agriculture; products typically produced outside of the city, thus requiring a significant amount of energy to bring from seed to table, offsetting the natural carbon cycle of producing, consuming, and returning waste to the same ecological system (Despommier, 2010).

In addition to this carbon deficit, the buildings themselves represent a significant bank of energy, both in the embodied resources as well as the consumption of new energy necessary to keep the building suitable for habitation.
Through building-integrated agriculture, the excess of architecture offers the possibility for narrowing the metabolic gap in the carbon cycle: greenhouses are a well-established technology that guarantees safe and reliable year-round food production (Despommier, 2013). Both architecture and ecological systems thrive on surplus and abundance (Moe, 2014), affording more ecological power through strategic design. Architects function in this design role, specifying large amounts of energy, materials, and information in the context of a building; if this awareness could extend to the deeper metabolic cycles occurring within the buildings they design, an opportunity arises in reinterpreting buildings as resource generators rather than resource consumers.

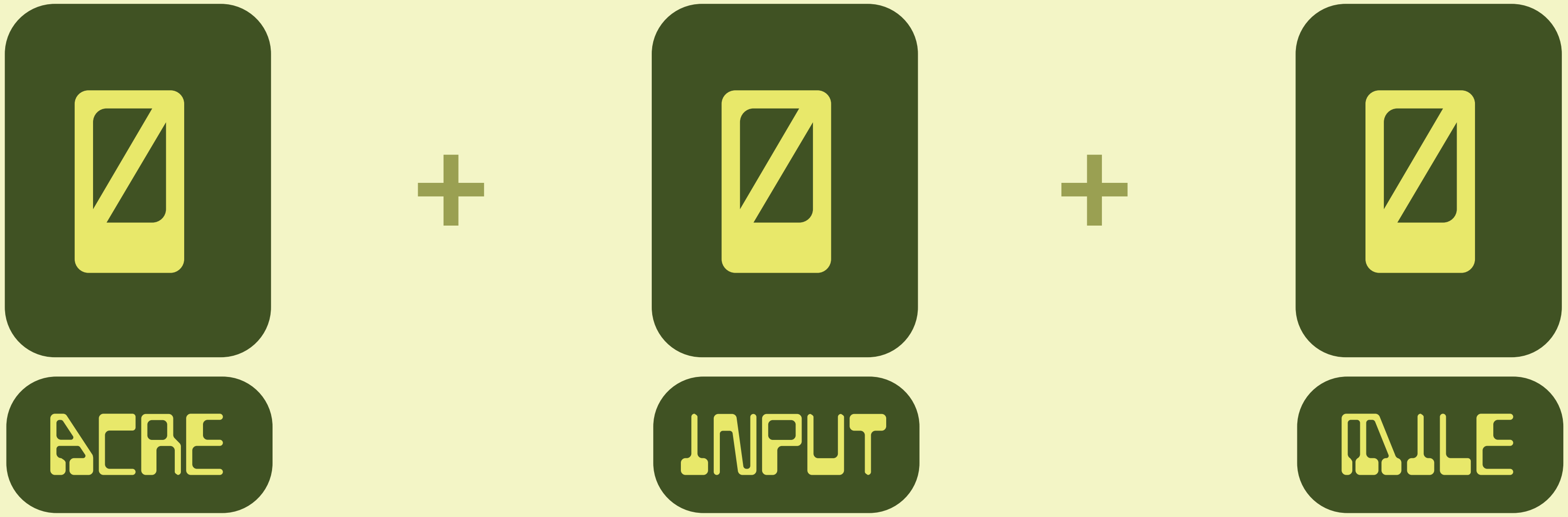


Fig. 3.7: Zero Sum Game

Architecture can grow if the object of architecture is not limited to objects alone (Moe, 2020), but to the systems and surplus involved through the process of production and consumption. Stacking agriculture onto buildings is one way to shift this paradigm of the building as object to building as ecological expression, closing the metabolic gap between where food is produced and where it is consumed (Despommier, 2013; Steel, 2012) while expanding the value of the built environment housing it.

In the context of this framework, the goal is to implement design decisions which make the most of our most abundant resource: solar radiation. Design is a delicate balance, and this strategy can impact other factors, including heat gain, glare, and elevated cooling costs depending on the region and building. However, it's a strong position, and for plants that need large quantities of light day in and day out, it's a good place to begin.

Net-Zero Agriculture

We're already working toward net-zero energy buildings, but what if we had net-zero agriculture as well? There are a number of movements within agriculture challenging the current technological determinism of large-scale monoculture. Zero-input agriculture seeks to minimize the intervention of external application of resources such as nitrogen-based fertilizers or pesticides in favor of co-planting and polyculture (Thissen, 2021, Uphoff 2003). Monoculture oversimplifies natural systems, requiring massive inputs of resources to maintain balance; zero-input agriculture trades single species optimization for biodiversity, reducing the need for dependence on external resources within the system.

This idea is not new to agriculture: Pre-Columbian agricultural practice considered the entire ecosystem, resulting in sustainable cycles which lasted for thousands of years (Mann, 2005). Nature was not something that competed against food production but was persuaded to carry the bulk of the labor in strategic ways (Graeber, 2021). Greenhouses offer similar potential, but by mimicking the cycles of natural systems while decoupling agriculture from seasonal shifts or soil-based inputs, new modes of closed agriculture can emerge.

The shift away from soil-based farming methods is tangential to a similar movement in agriculture, zero-acreage agriculture, sometimes called Z-Farming (Thomaier, 2014). Zero-acreage agriculture shares many similarities with building-integrated agriculture, with an emphasis on using wasted space in and on buildings. Building-integrated agriculture tends to emphasize symbiotic benefits in the built environment which are gained by coupling a greenhouse with a building, while zero-acreage farming uses space as a resource, and the emphasis is shifted on the non-use of land (Thomaier, 2014), which often allow previously farmed agricultural parcels to be reforested (Despommier, 2013).

Finally, zero-mileage agriculture narrows the allowed distance a given agricultural product may travel to under one hundred miles. Due to large-scale monoculture practices, food often travels thousands of miles between the point where it was grown and the end point of consumption. The energy required to transport this food, typically under refrigeration, is significant and adds to the metabolic debt incurred within agriculture.

By combining these three zero-method agricultural practices, which currently stand separately but may offer new potential and innovation when combined into a larger paradigm for design, represent a shift in thinking. A move away from consumption and maximizing profit and product and toward something that takes a less-is-more approach. At the core, each of these three ideas share the common thread of reduced scale, and in doing so, directly challenge the way agriculture is currently practiced.

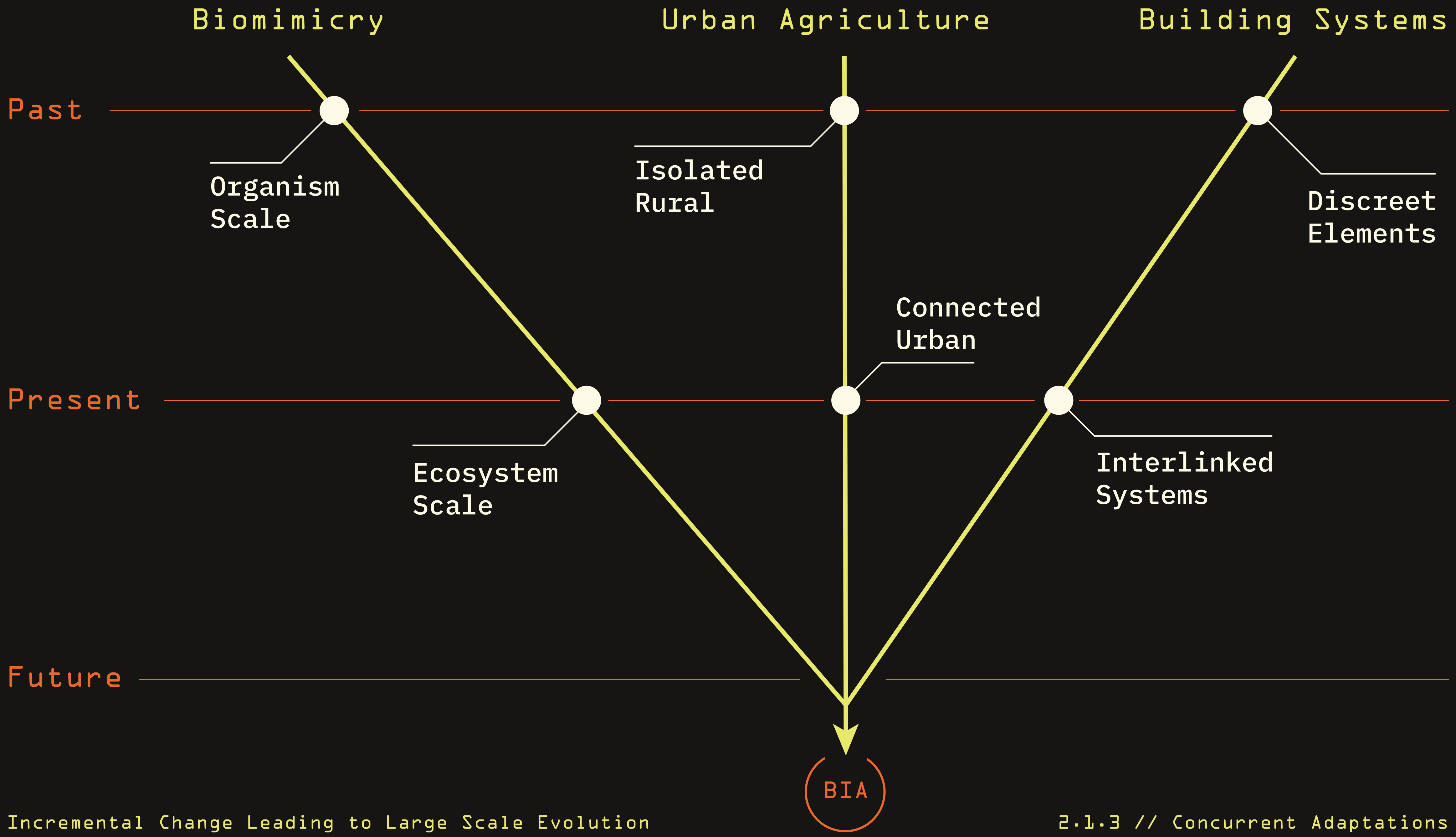


Fig. 3.8: Concurrent Adaptations

Adaptive Architecture

Mapping the shared trajectories of biomimicry, urban agriculture, and integrated systems design demonstrates a trend from small to large-scale thinking. Over the last decade, biomimicry as a field within architecture has expanded from discreet elements to ecological systems in scale. This reflects natural processes, resulting in architecture that respects the global cycles of energy and resource balance inherently present in the system it mimics (Exteberria, 2017), resulting in meaningful, systematic translations of ecological and biological scientific knowledge into the built environment (Armstrong, 2009).

Greenhouses are moving increasingly closer to metropolitan centers to take advantage of transportation and skilled labor (Agritecture, 2021), resulting in increased interest in how these structures could share space with the urban built environment (Gould, 2012) through innovative integration methods. Regarding building systems, there is recognition that current architectural practices often undermine sustainability, offering a new awareness that brings a shift towards design as an interconnected whole where problems are addressed via the integration of several other technologies or disciplines (Lassen, 2021).

The application of systems thinking to architectural practice creates a context ripe for agricultural integration: systems theory frames collections of interdependent components as a series of relationships and consequences sharing the same significance as the individual components themselves, emphasizing the emergent properties that result from these relationships (Vassallo, 2017). Individually, these changes indicate progress across large disciplines and areas of research. When compared side by side, they indicate a new story: a context with a strong bias for the continued upwards trend in building-integrated agricultural design.
In the context of this project, the concurrent development of biomimicry, urban agriculture, and integrated systems design signifies a paradigm shift towards regenerative and sustainable design practices. Architects are increasingly embracing nature not as an obstacle to overcome, but as a mentor, leveraging its wisdom to create buildings that are not only aesthetically pleasing but also ecologically responsible.

By integrating agriculture into urban spaces and optimizing various systems within the built environment, architects are striving to create resilient, resource-efficient, and livable cities that promote human well-being and environmental harmony.

IV. Design Framework

Architecture as Agriculture

Architecture as Agriculture

Chapter 4: Design Framework

4.1 Building Integration

Greenhouse integration in and on new or existing buildings is still relatively new, especially in North America (Appoloni et al. 2021). From an agricultural perspective, urban settings are considered to be extreme environments and require protected agricultural interventions to facilitate growing (McCartney et al. 2018), but as an innovative method of farming, building integrated CEA has not been adequately addressed in regard to research from a built environment perspective (Kalantari et al. 2017). As CEA continues to evolve and develop, this interaction with the built environment creates new opportunities for urban farms that did not exist with conventional agricultural methods, including vertical greenhouses, which make use of space in high-rise buildings (Kalantari et al. 2017).

While various forms of greenhouse integration have been explored by architects and design schools, the aesthetic integration between building and greenhouse remains largely unexplored (Specht 2017). Ling et al. (2018) observe that the role of aesthetic function between urban agriculture and buildings is one of the most critical challenges, as a proposed greenhouse design must not only perform as a growing space but also add value to the host building while simultaneously offering an architectural design solution which is capable of shifting public views of agriculture towards something capable of being supported within an urban setting. It is not difficult for architects and other built environment professionals to see the proposed value of an integrated greenhouse that share metabolic flows (Sanyé-Mengual et al. 2016) which tighter or closes existing resource loops shared between the two structures.

RTG vs i-RTG Subtypes

A rooftop greenhouse (RTG) is a greenhouse, typically a high-tech gutter-connected commercial facility, which is placed on the flat roof of a host building. The greenhouse maintains its own systems of heating, cooling, water management, and ventilation which are independent of the building it is constructed upon. In contrast, a novel form of this is the i-RTG or integrated rooftop greenhouse. This type of greenhouse is also typically a high-tech glasshouse with gutter-connected bays, but rather than exist independently of the host building, it adopts an ecological model for a design that exploits symbiotic relationships between shared resource flows (Nada et al. 2017). The i-RTG, according to Nadal, exhibits four key criteria:

1. The symbiosis between rooftop and building structure by means of reducing residual resources flows of energy, water, and CO2.
2. Interconnectivity of those flows such that the greenhouse is not an isolated element, but a necessary part of the entire greenhouse/host building ecosystem.
3. Reduction of environmental impact and increased efficiency.
4. Use of rooftop spaced to generate food self-sufficiency in an urban setting.

Rooftops offer significant potential for urban agriculture, given that they occupy between 21-26% of urban environments (Nadal et al. 2017), although not all buildings are suitable hosts. Additional layers of value may further enhance the efficiency and benefit of an RTG, including the addition of photovoltaic cells or rainwater harvesting (Getter et al. 2006).

Integrated Systems

Research on an integrated greenhouse within a lunar module demonstrate how deeper integration, including systems that share common resource delivery systems such as ventilation and wastewater management offer better performance and efficiency than as separate entities (Sadler et al. 2009). Both buildings and CEA greenhouses require high thermal and power input during peak operational periods, and in turn both waste energy via the building envelope, especially when there is poor insulation, during overheating and during times of high solar irradiance (Muñoz-Liesa et al. 2020).

The benefits of shared energy flows are already well supported in current literature, new research is expanding the scope of integration to look at flows such as ventilation and water. It has been found that the exhaust ventilation of an integrated greenhouse poses no health risks or allergies to humans (Ercilla-Montserrat et al. 2017), and can be recaptured and recirculated into a building as already tempered air, oxygen-rich due to the consumption of CO2 by plants inside the growing space. Harvesting low-grade building waste energy for use in the greenhouse, and vice versa when conditions are necessary represents one method of integration that takes two isolated systems and decarbonizes them into an inclusive model which looks at the two spaces in a more holistic manner (Muñoz-Liesa et al. 2020)

Design Factors

In addition to the various structural, envelope, and environmental systems that a greenhouse shares in common with the built environment, there are a number of discrete design factors which are directly related to performance and fall under the scope of architectural design. These range from programming (farming/operational typologies) and site analysis (climate, geographic, and urban data) to building-specific performance metrics including wind and snow loads to broader environmental factors such as life cycle analysis (LCA) or social or economic impacts. Because of these discreet factors, which impact building performance in many ways that overlap building design for human occupants, von Elsner notes that "despite the large number of innovations applied in the present day greenhouses, no design can be considered the perfect unique solution. Greenhouse construction must meet local needs and climatic conditions. For this reason, the standardization of greenhouses at a European level involves difficult technical, economic, social and legal problems (2000)"

Architects, because of their familiarity with code, occupancy comfort, spatial programming, and their ability to successfully navigate complex systems that span from design, permitting, construction, community engagement, and budgetary constraints, are uniquely suited to engage the complexity of the additional design considerations these factors bring up when looking at an integrated greenhouse design.

Operational Typologies

Thomaier et al. (2015) define five operational typologies for urban agriculture; these typologies may
be extended to greenhouse operations, given their identity as built structures, and thus do not share the same typological parameters of conventional, soil-based agriculture operations which have remained largely unchanged for thousands of years (Despommier 2013). These five typologies are modeled after Cohen et al. (2012) original five typologies for urban farms, which has been widely adopted as the standard model for urban agriculture but includes open, soil-based methods of agricultural such as community gardens. Specht narrowed this by overlapping the original five typologies with their interaction to the built environment, including greenhouses.

Commercial: The primary purpose of this operational type is to exist as an economically viable operation, usually falling into one of two subcategories: retail-affiliated or independent (Thomaier et al. 2015). Retail-affiliated operations supply a single retailer or stakeholder, such as a restaurant, with products, while an independent operation is responsible for finding and managing different buyers without the expectation of exclusivity. High tech greenhouses are typically commercial operations, given the high investment cost over other greenhouse types (Ruijs et al. 2020), with the added benefit that these costs may be recouped via a controlled environment with consistent production capabilities (Zisis et al. 2019), which are no longer dependent on exterior climate conditions.

Research & Innovation: Greenhouses are frequently found connected to academic institutions for the purposes of research (Thomaier et al. 2015), especially for the purposes of closed environment agriculture. Greenhouses themselves represent an intersection of numerous fields and disciplines ranging from agriculture to engineering, and due the high costs associated with constructing a fully closed environment necessary for rigorous research, benefit from funding from the partnered institution while being free of the need for consistent production.

Social & Educational: Educational greenhouses differ from research-oriented operations by shifting the focus to the education of those involved in the operation, or often in the case of greenhouses associated with botanical gardens or non-profit organizations, larger community engagement regarding food production and agriculture, including topics related to food justice and security (Sanyé-Mengual et al. 2016). Instead of commercial sales, the products are typically offered to the volunteers and operators who run the greenhouse (Goodman et al. 2019), or utilized in a connected cafeteria as a method of extending the educational process to the end point of consumption (Thomaier et al. 2015).

Image Oriented: These greenhouses serve as a value-additive component of another operation, such as a restaurant or grocery store, in which the products of the greenhouse supplement the vision and goals of the primary business, offsetting the production requirements of the greenhouse itself in exchange for other forms of value (Thomaier et al. 2015).

Living Quality: Greenhouses which are designed not as production facilities, but as integrated spaces within urban mixed-use buildings (Thomaier et al. 2015), offer residents and users the opportunity to produce and engage with their own food production as a form of amenity to the parent space or community.

External Environment

In regards to external factors such as site and climate, greenhouse design is not much different from any other structure: considerations include drainage and storm water management, circulation and accessibility (especially for commercial operations, which will likely require loading/unloading access), and solar access including potential overshading from future buildings (USBG Manual, 2019).

Climate is a central factor in greenhouse design, and represents both technical and economic challenges for the designer (von Elsner et al. 2000) due to the highly diversified and locally dependent microclimates. This factor may be compounded when the greenhouse is located in or around an urban setting, which creates additional challenges as well as some passive benefits in design. Commercial greenhouses in urban settings can often benefit from reduced wind loads, which represent the greatest external forces acting on a greenhouse structure (Muñoz-Liesa et al. 2021).

The orientation of the greenhouse on the site itself is also critical, as proper orientation, along with the use of adequate thermal mass, shading, and material selection can significant-

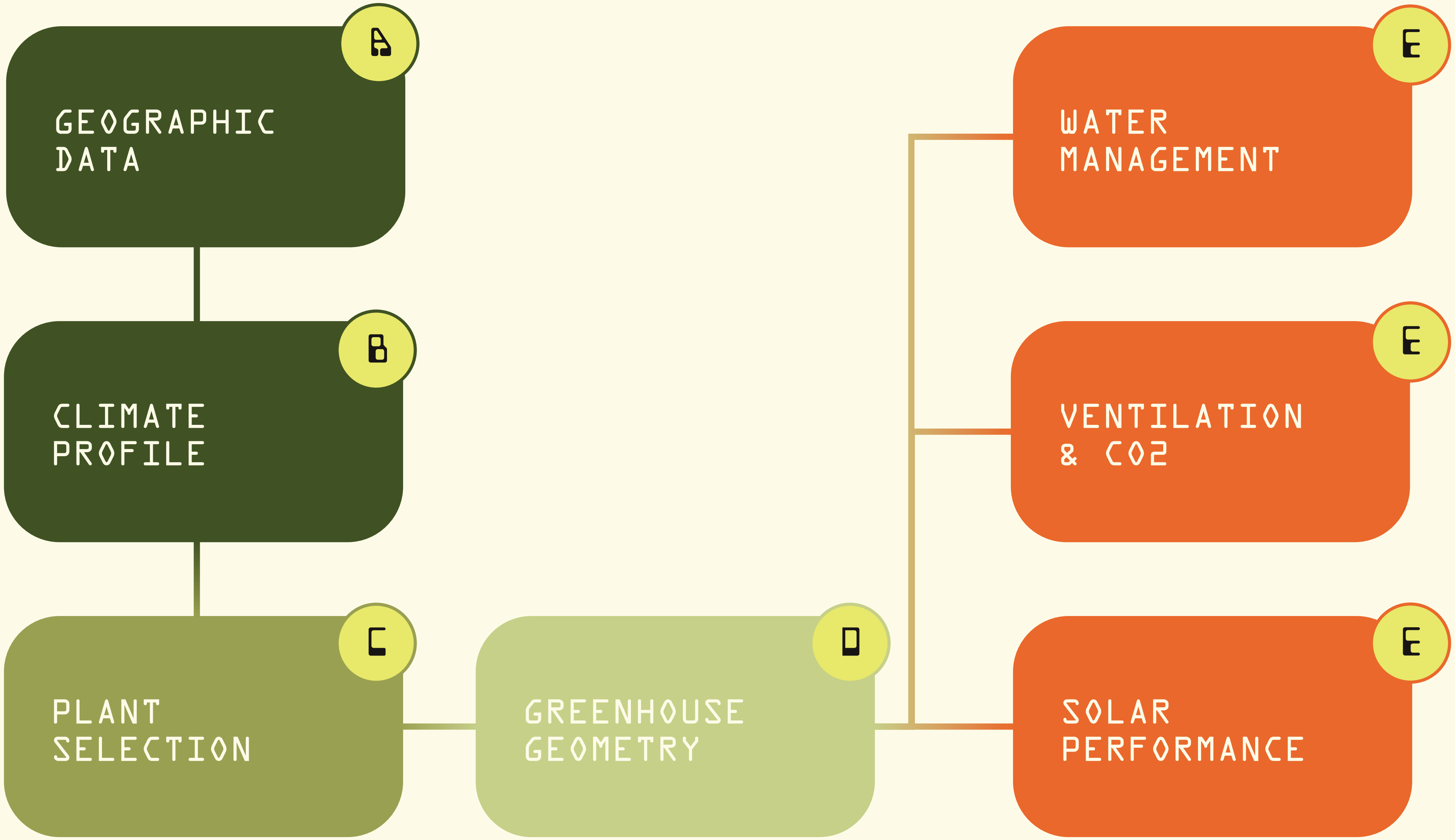


Fig. 4.1: Modules

ly reduce thermal loads in a CEA greenhouse to the point passive or active systems become secondary (Engler 2021). Basic guidelines suggest in locations north of 40 degrees latitude, the long axis runs east to west, placing the long side of the structure to the south for ideal solar gain (USBG 2019). For locations south of 40 degrees latitude, the long axis is ideally set along a north-south axis, which reduces internal shading from structural elements and exposes the ridge line to prevailing winds for ventilation during the warmest months (USBG 2019).

Social and Economic Considerations

Increased capital investment, which has already been noted, is a common challenge of modern greenhouses, which typically involve sophisticated environmental controls and use of performance materials (Engler 2021). Because of this, the average age of a profitable CEA farm is 7 years, while the average age of an unprofitable farm is 5; these numbers align with other disruptive industries, such as electric car manufacturer (Engler 2021), and demonstrate both the innovative and voaltive state of commercial greenhouse farming.

Beyond the technical challenges with urban greenhouse design, there are a number of social factors which can impact the design process. Historically, urban planners have not supported the presence of farming within the city due to the incompatibility of agriculture with urban life (Goodman et al. 2019). Greenhouses represent a shift in the method of production to a form which is compatible with the modern urban setting, however zoning regulations and negative public perspectives on rural activities such as farming remain firmly entrenched (Specht et al. 2017). Architects stand at a unique crossroads in this discussion, given their ability to engage with both the technical aspects of greenhouse design as well as the social considerations and design values necessary to integration into the urban fabric in a meaningful way.

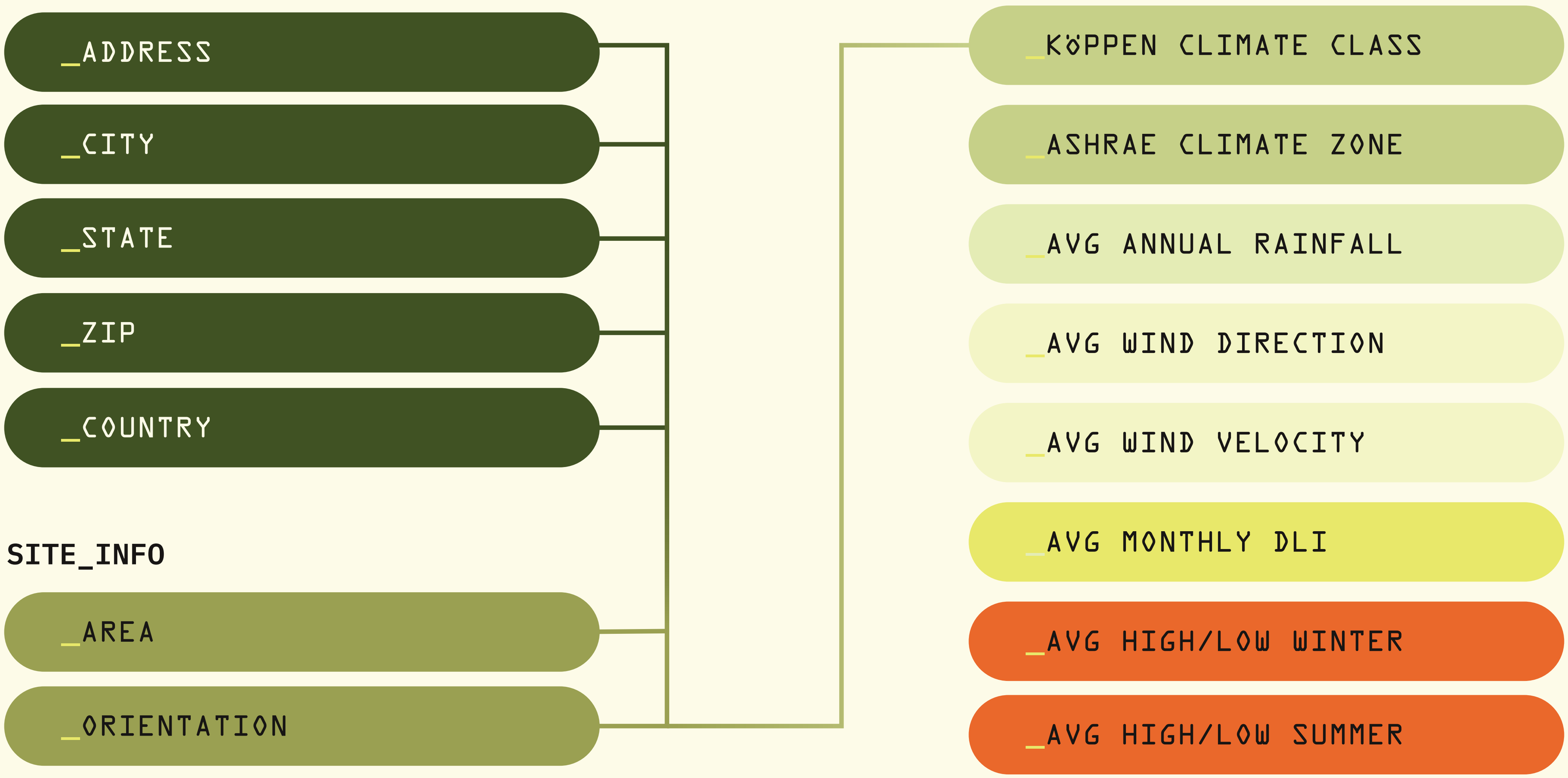
4.2 Integrated Design Framework

The integrated design framework prioritizes various factors to create sustainable and functional spaces that seamlessly blend agriculture with built environments. The framework begins with a comprehensive analysis of geographic data, including climate location and weather conditions, to inform the selection of suitable plant species and cultivars. The spatial geometry and design of the structure are then carefully considered, optimizing the arrangement of planting areas and vertical farming systems to maximize sunlight exposure and accessibility while ensuring an aesthetically pleasing environment. Solar performance is a key aspect, balancing the lighting needs of both plants and occupants by strategically placing glazing systems and incorporating shading devices to manage potential thermal gains.

Water management plays a crucial role in the framework, emphasizing rainwater harvesting and efficient irrigation systems to minimize water usage while meeting plant hydration needs. The symbiotic ventilation aspect addresses the exchange of CO2 and oxygen, designing ventilation systems that promote airflow and fresh air circulation between plant areas and human-occupied spaces. Technological integration incorporates sensor networks and automation for monitoring environmental parameters and controlling lighting, irrigation, and climate systems in real-time. Lastly, a focus on life cycle analysis and sustainability ensures the overall environmental impact is minimized, encompassing sustainable material choices, energy-efficient systems, and waste reduction strategies.

Carefully consideration of all these factors will support the development of a balanced system, with considerations for both plant and human occupants, a delicate task to manage for integrated design projects. The following sections will now explore what the integrated framework looks like based on the following sections:

Fig. 4.2: Geographic + Climate Data



_ADDRESS

_CITY

_STATE

_ZIP

_COUNTRY

SITE_INFO

_AREA

_ORIENTATION

_KÖPPEN CLIMATE CLASS

_ASHRAE CLIMATE ZONE

_AVG ANNUAL RAINFALL

_AVG WIND DIRECTION

_AVG WIND VELOCITY

_AVG MONTHLY DLI

_AVG HIGH/LOW WINTER

_AVG HIGH/LOW SUMMER

GEOGRAPHIC_DATA

CLIMATE_DATA

Geographic & Climate Data

This section begins by analyzing local climatic conditions, including temperature, humidity, precipitation patterns, and seasonal variations. Consideration should be made for the impact of climate on plant selection, growth requirements, and overall building performance.

Plant Selection

The next section determines suitable plant species and cultivars based on climate, available resources, and desired outcomes (e.g., food production, aesthetics, air purification). Additional factors that should be considered include light requirements, temperature tolerance, water needs, and growth habits. This stage also determines a monoculture versus polyculture planting strategy.

Greenhouse Geometry

In this section, a spatial configuration that optimizes the integration of agricultural elements within the built environment is more fully developed. This takes into account arrangement and organization of planting areas and farming systems, optimal sunlight exposure, panchromatic needs, and aesthetics.

Solar Performance

This section requires the balance between the lighting needs of plants and human occupants and the thermal gain that accompanies it. The use of daylighting analysis tools to determine appropriate lighting, as well as assess the need for shading devices and supplemental lighting should also be addressed in this section.

Water Management

Water management includes rainwater harvesting, water storage, and irrigation systems. Considerations include annual rainfall patterns, evaporation rates, planting requirements, and the irrigation systems. For hydroponics systems, systems will need to be defined as open or closed and include strategies for wastewater management and ideally, recycling via a recirculating system.

Ventilation & CO2

In mixed use greenhouses, ventilation requires balancing the relationship between plants and humans. Design ventilation systems that promote airflow and facilitate the circulation of fresh air between plant areas and occupied spaces can help support symbiotic exchanges, although climate has a large impact on the outcome and depending on if people and plants inhabit the same space, this can create conflicting goals around thermal comfort vs ideal growing conditions.

Fig. 4.3: Plant Selection

MONOCULTURE CEA

Romaine Lettuce

Day: 50-70 degrees F
Night: 45-55 degrees F
70-80% Relative Humidity
DLI 14-16

Tomato

Day: 70-82 degrees F
Night: 62-64 degrees F
60-70% Relative Humidity
DLI 30

Basil

Day: 65-84 degrees F
Night: 52-65 degrees F
70-80% Relative Humidity
DLI 29

VS.

POLYCULTURE CEA

59-77 Degrees F / 80% Humidity

- Romaine Lettuce
- Butter Lettuce
- Swiss Chard
- Spinach
- Kale
- Celery
- Green Onion
- Chives
- Basil
- Cilantro
- Dill
- Mint
- Parsley
- Rosemary
- Sage
- Oregano

4.3 Geographic & Climate Data

The core of the integrated design framework seeks to go beyond simple spatial arrangements and site analysis or plant arrangement and considers what a deep integration to the surrounding context and climate would look like.

Total Area: The total area available for integrated agriculture plays a significant role in determining the scope and scale of the design. Designers must consider the available land area for planting beds, greenhouses, or vertical farming systems. The area requirements will vary depending on the desired plant selection, production goals, and the integration of other functional spaces within the building.

Orientation: The orientation of the building and planting areas is crucial for maximizing sunlight exposure and energy efficiency. By analyzing the site's solar path and understanding the movement of the sun throughout the day and across different seasons, architects can optimize the placement of glazing systems, skylights, and shading devices. This ensures that plants receive adequate natural light while minimizing heat gain and glare. Additionally, the orientation of the building can also be designed to take advantage of prevailing winds for natural ventilation and temperature regulation.

Surrounding Context: Understanding the surrounding context of the site is crucial for integrating the agricultural design seamlessly into the environment. Factors such as neighboring buildings, landscape features, and the overall urban context can influence the design approach. Architects should consider the visual integration of the agricultural elements within the site context, ensuring a harmonious relationship with the surrounding built and natural environment.

Location Data: To further refine the location data, architects can incorporate specific variables that provide a deeper understanding of the site's climatic conditions. This includes the Köppen climate classification, which categorizes climates based on temperature and precipitation patterns. The ASHRAE climate zone classification system provides additional insights into energy use and building design considerations specific to the region. Average annual rainfall data helps determine irrigation needs and water management strategies, while average wind direction and velocity data aids in designing effective windbreaks and harnessing natural ventilation. Average monthly daily light integral (DLI) for the region helps assess the available light for plant growth throughout the year. High and low temperature and humidity data provide valuable information for designing climate control systems and ensuring optimal growing conditions.

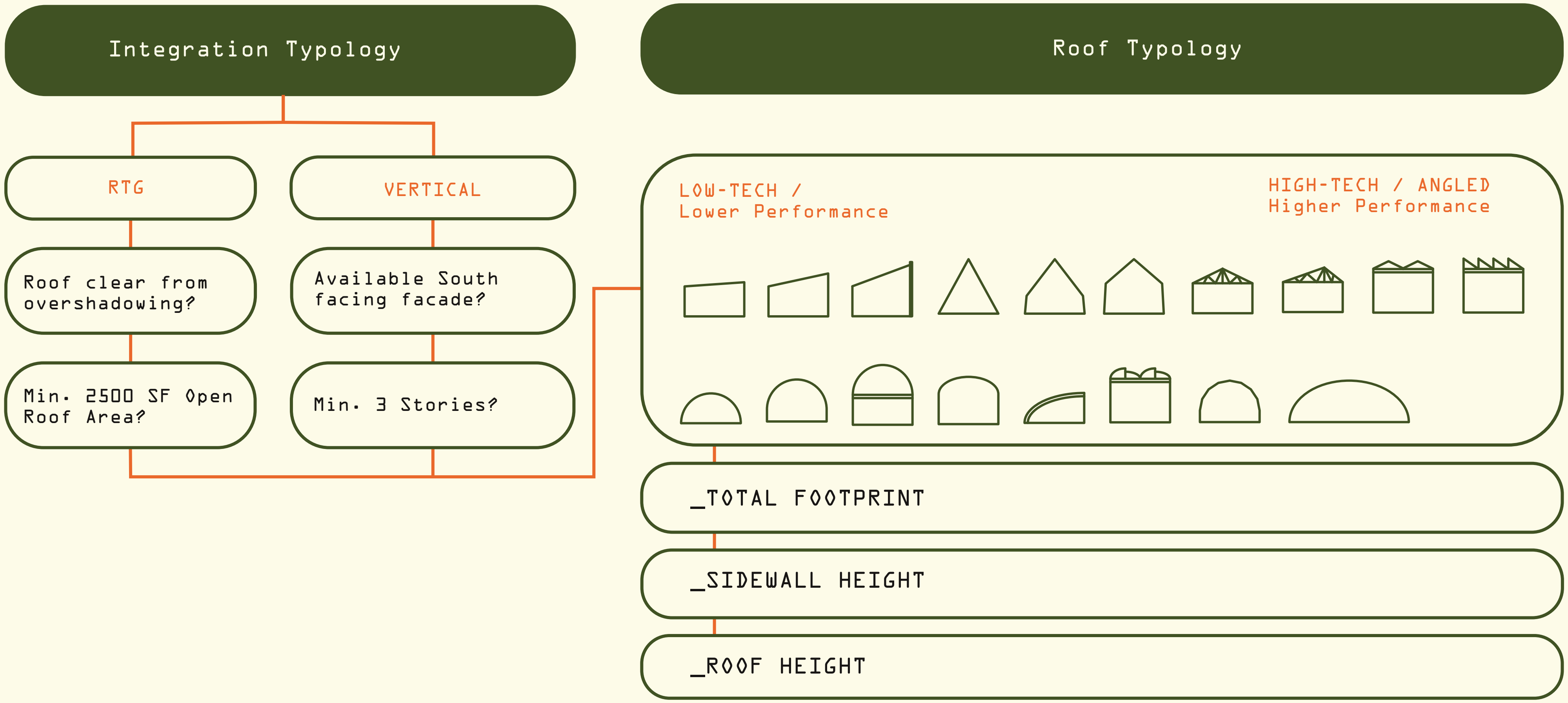
By incorporating these design considerations and refining the location data, architects can create integrated agricultural designs that are responsive to the site's context and climatic conditions. This approach allows for the optimization of the spatial geometry and design, resulting in buildings that seamlessly integrate with the surroundings, maximize energy efficiency, and provide an optimal environment for plant growth.

4.4 Plant Selection

The plant selection component of the integrated design matrix considers not just plant selection, but also polyculture versus monoculture in controlled environment agriculture. This section focuses on the decision of whether to design a controlled environment optimized for maximum production of a single plant species or to create a more forgiving controlled climate that accommodates a range of plant species with varying environmental requirements.

Polyculture: Polyculture prioritizes the cultivation of multiple plant species within the same environment while meeting consumer demand for diversified food (Rufí-Salís, 2020). Due to the urban setting of many integrated greenhouses, creating a controlled environment that accommodates a range of

Fig. 4.4: Geometry



Integration Typology

RTG

Roof clear from overshadowing?

Min. 2500 SF Open Roof Area?

VERTICAL

Available South facing facade?

Min. 3 Stories?

Roof Typology

LOW-TECH /
Lower Performance

HIGH-TECH / ANGLED
Higher Performance

_TOTAL FOOTPRINT

_SIDEWALL HEIGHT

_ROOF HEIGHT

environmental conditions suitable for different plant species can foster a more balanced ecosystem and support food insecure regions (Moran, 2022).

Monoculture: As the name suggests, monoculture involves growing a single plant species, which is more commonly found in large scale intensive CEA operations that require optimized production of a single species. This approach allows for precise tuning of the environmental conditions for a specific plant species. Since this method enables tailoring the greenhouse systems, including lighting, temperature, humidity, and nutrients for peak production, monoculture systems are best suited when there is a high demand for a specific crop, such as leafy greens or herbs, and require highly controlled and consistent environmental parameters to achieve maximum yield and quality.

When deciding between polyculture and monoculture, architects must carefully consider the objectives and priorities of the integrated agricultural design. Polyculture may be more suitable when the aim is to create a diverse and sustainable ecosystem that supports multiple plant species, promotes ecological balance, and reduces the risk of crop failure due to pests or diseases. This approach requires a broader range of environmental conditions, which can be more forgiving in terms of maintaining a controlled climate.

On the other hand, monoculture may be preferred when the primary goal is to maximize the yield and quality of a specific crop. This approach allows for precise control over environmental variables, ensuring optimal conditions for the targeted plant species. Monoculture systems often require more intensive monitoring and management to maintain the desired environmental parameters consistently.

Ultimately, choosing between polyculture and monoculture depends not only on spatial constraints, but other factors including consumer demand and resources such as available daylight to the agricultural space to ensure adequate DLI. Designers need to balance both approaches, consider the overall sustainability, biodiversity, and productivity goals of the project while factoring in the overall building and possible limitations of the controlled environment systems that will be employed in the design.

4.5 Greenhouse Geometry

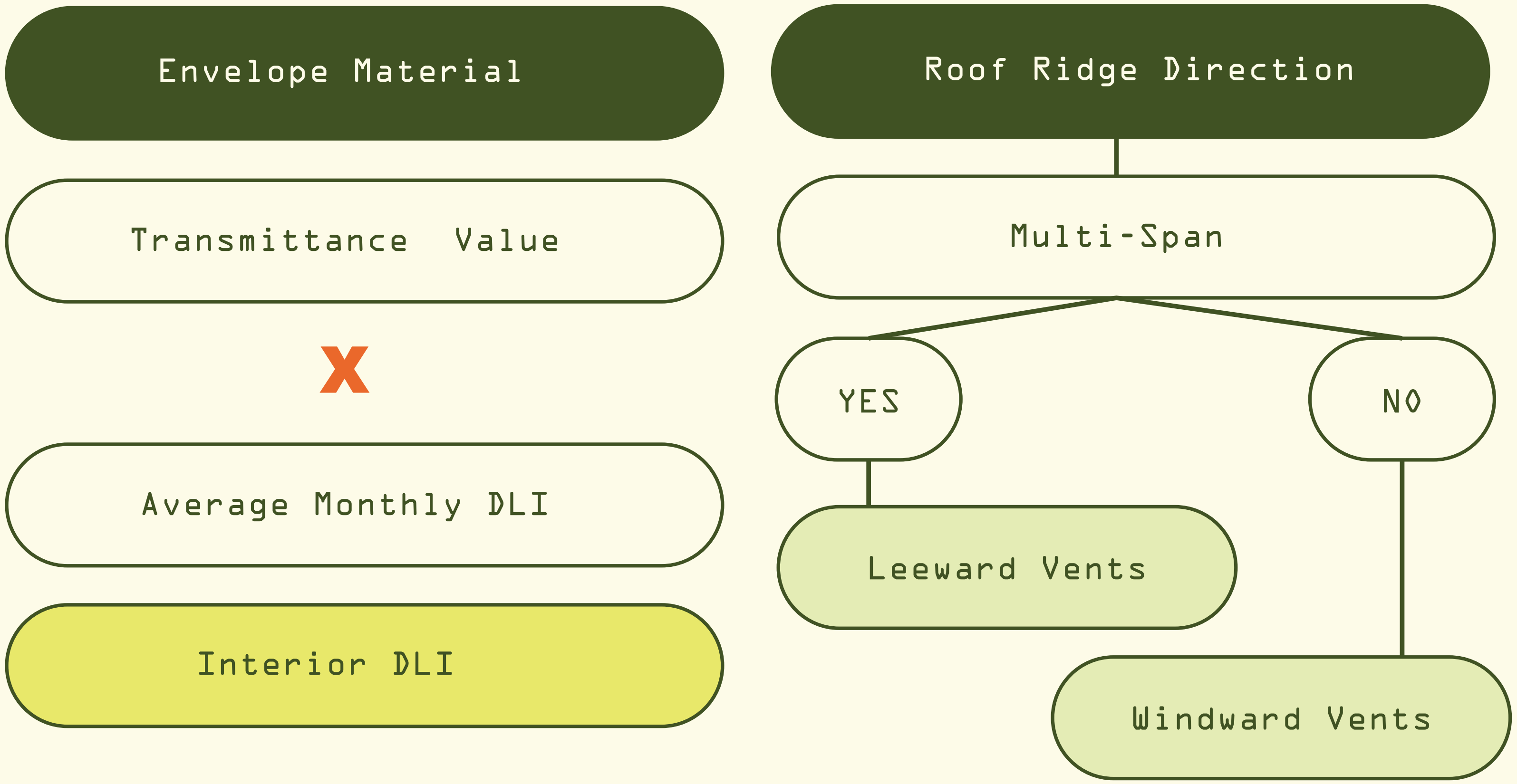
The greenhouse geometry component of the integrated design matrix encompasses considerations for the agricultural integration typology, specifically the choice between an integrated rooftop greenhouse or a vertical wall farm. This decision is influenced by factors such as the building's height, available floors, and the presence of an open and accessible roof or a south-facing wall.

Integrated Rooftop Greenhouse (iRTG): If an integrated rooftop greenhouse is selected, the main factor driving the geometry is rooftop space, since it needs to be large enough to justify incorporating a greenhouse, as well as capable of supporting both structure and agricultural operations. Structural considerations such as the load-bearing capacity of the host building, structural arrangement of the greenhouse members, and accessibility all need to be taken into consideration.

The typology determining the roof shape is also important, since it largely determines how light penetrates the structure. Roof typologies fall on a spectrum between low-performance/low-technology, which begin with a flat roof shape, and move toward high-performance/high-technology complex typologies such as the Venlo style. Selection depends on a number of factors, including the desired level of environmental control, target energy efficiency, and aesthetic integration with the overall building design.

Vertical Farm: For buildings with a large, south-facing wall, vertical farms are a valid option. Vertical farming is useful for

Fig. 4.5: internal Systems



Envelope Material

Transmittance Value

x

Average Monthly DLI

Interior DLI

Roof Ridge Direction

Multi-Span

YES

NO

Leeward Vents

Windward Vents

implementing growing systems where the roof is not available or where interior programming benefits from plants filtering light at an exterior wall, such as curtain glazing system. In addition to a suitable south-facing wall, space is another significant factor, since in addition to traditional building systems for irrigation and plant support are also necessary, making MEP coordination a significant task for this typology.

Regardless of the typology, one of the primary driving factors in any design is total available footprint for the growing area. This metric involves assessing the available roof or wall area and considering any potential obstructions or limitations that may affect cultivation activities. The maximum height of the sidewalls and the height and potential slope of the greenhouse roof (in the case of a rooftop greenhouse) also need to be established, since these factors will influence the spatial configuration and volume of the integrated agricultural space.

Designers should balance the functional requirements of the agricultural space with the overall building design and aesthetics. Selected typologies should align with the building's architectural language, complementing both its form and purpose. These aesthetic considerations need to be balanced with environmental decisions that look at sustainability not as an external object, but as something that arises from the building function and guided by local climate.

4.6 Internal Systems

The internal systems component examines factors arising as a result of primary choices like roof shape and geographical location. These factors include the selection of envelope material and roof ridge direction, both of which may have a profound impact on available DLI for the space. These variables play a crucial role in optimizing the internal environment, maximizing daylight transmission, and facilitating natural ventilation.

Envelope Material: The envelope material chosen for a greenhouse is an important design consideration, since it affects the transmittance value and influences the amount of daylight entering the agricultural space. Designers can choose from a range of materials, such as glass, polycarbonate, or ETFE (ethylene tetrafluoroethylene). Each material has different properties related to light transmittance, insulation, and durability. The transmittance value of the selected material should be carefully evaluated to ensure optimal light penetration for plant growth while considering energy efficiency and heat gain control. A balance must be struck between maximizing daylight availability and minimizing potential overheating.

Roof Ridge Direction: The design of the greenhouse roof ridge is another critical aspect to consider. Architects have the choice between a single-span or multi-span configuration, each with its own advantages and considerations. The orientation of the roof ridge can impact the internal shading and the overall efficiency of the greenhouse. By strategically positioning the roof ridge in relation to the sun's path, designers can optimize the distribution of sunlight and control the shading within the agricultural space (Appelbaum, 2020).

Additionally, the inclusion of leeward or windward vents can facilitate natural ventilation and airflow management, which helps regulate temperature, humidity, and carbon dioxide levels within the space (Villagrán, 2019), reducing the reliance on mechanical ventilation systems or electrical fans.

Natural Ventilation and Airflow: Natural ventilation is an important consideration in integrated greenhouse design, especially in structures built in hot or humid climates where overheating is a concern. By incorporating leeward and windward vents and strategically positioning them, architects can take advantage of prevailing winds to facilitate airflow. Natural ventilation helps maintain a favorable climate for both plants and occupants, ensuring an adequate supply of fresh air and reducing the reliance on mechanical systems. However, it is

This integrated design matrix proposes a holistic and comprehensive paradigm for creating a symbiotic building which prioritizes the health and comfort of both human and plant occupants, while responsibly adapting to the site and climate, encompasses various design considerations.

essential to consider the local climate conditions, wind patterns, and potential external factors that may affect airflow. In some cases, supplemental mechanical ventilation, such as fans, may be necessary to enhance airflow and ensure proper ventilation if natural ventilation alone is insufficient.

By considering envelope material selection, roof ridge direction, and natural ventilation strategies, architects can create an internal environment within the integrated agricultural space that optimizes daylight penetration, manages shading, and promotes natural airflow. These design variables contribute to the overall sustainability, energy efficiency, and comfort of the space, providing an ideal environment for plant growth and human occupancy.

4.7 Summary

This integrated design matrix proposed a holistic and comprehensive paradigm for architectural design, prioritizing the health and comfort of both human and plant occupants while responsibly adapting to the site and climate

While not exhaustive, by carefully evaluating each element outlined in this design framework, architects and built environment professionals can create a harmonious and sustainable environment which takes a comprehensive approach to design, creating a symbiotic space that promotes the well-being of both human and plant occupants, while adapting responsibly to the site's characteristics and climate conditions.

V. Applied Design

The MicroArcology

The MicroArcology

Chapter 5: Applied Design

5.1 Design Concept

What would happen if we thought of a building not as an imposted inhabitant on a site, but as an ecological adaptation of the surrounding environment,

Using the integrated design matrix to the development of the concept of a MicroArcology involves a strategic approach that considers the unique characteristics of the site and the local climate. The goal is to create an environmentally responsive building design that prioritizes the well-being of both human and plant occupants while integrating agricultural elements that benefit the surrounding community.

The first step is to select a region, followed by a thorough analysis of a potential site. This includes understanding the orientation of the building, available total area, and surrounding context. Additionally, collecting and refining location data such as the Köppen climate classification, ASHRAE climate zone, average annual rainfall, average wind direction and velocity, monthly daily light integral, and high and low temperature and humidity data is essential for deciding which climate strategies to prioritize.

Once the preliminary site data has been collected and a program is developed, the plant selection process begins. Considering the specific climate conditions of each region will help specify a range of plant species that can thrive in the selected climate, with emphasis on striking a balance between plants optimized for maximum production in a controlled environment and those that can adapt to a broader range of environmental conditions.

Next, the building geometry should be designed to optimize the integration of agriculture. The MicroArcology should feature an integrated rooftop greenhouse, taking advantage of the abundant sunlight and open roof space for cultivation. The choice of greenhouse roof shape would depend on the desired performance level, considering factors such as the maximum daylight transmission, potential slope, and sidewall height. The design should also consider the total available footprint for the growing area and the number of floors available in the building.

Moving on to internal design variables, careful consideration should be given to the selection of envelope materials for the building. Opting for materials with appropriate transmittance values can maximize daylight entering the space while maintaining thermal performance. Furthermore, the roof ridge direction could be designed to facilitate natural ventilation, incorporating leeward or windward vents to enhance airflow and regulate temperature and humidity levels.

Throughout the design process, the environmental factors specific to the region such as average temperature and available daylight should be carefully addressed. This may involve incorporating shading strategies, thermal insulation, and efficient water management systems to mitigate the impact of high temperatures or scarce water resources.

By following this strategic framework and utilizing the design matrix as a guideline, the MicroArcology can evolve as an environmentally responsive building that harmoniously integrates architecture and agriculture. The symbiotic relationship

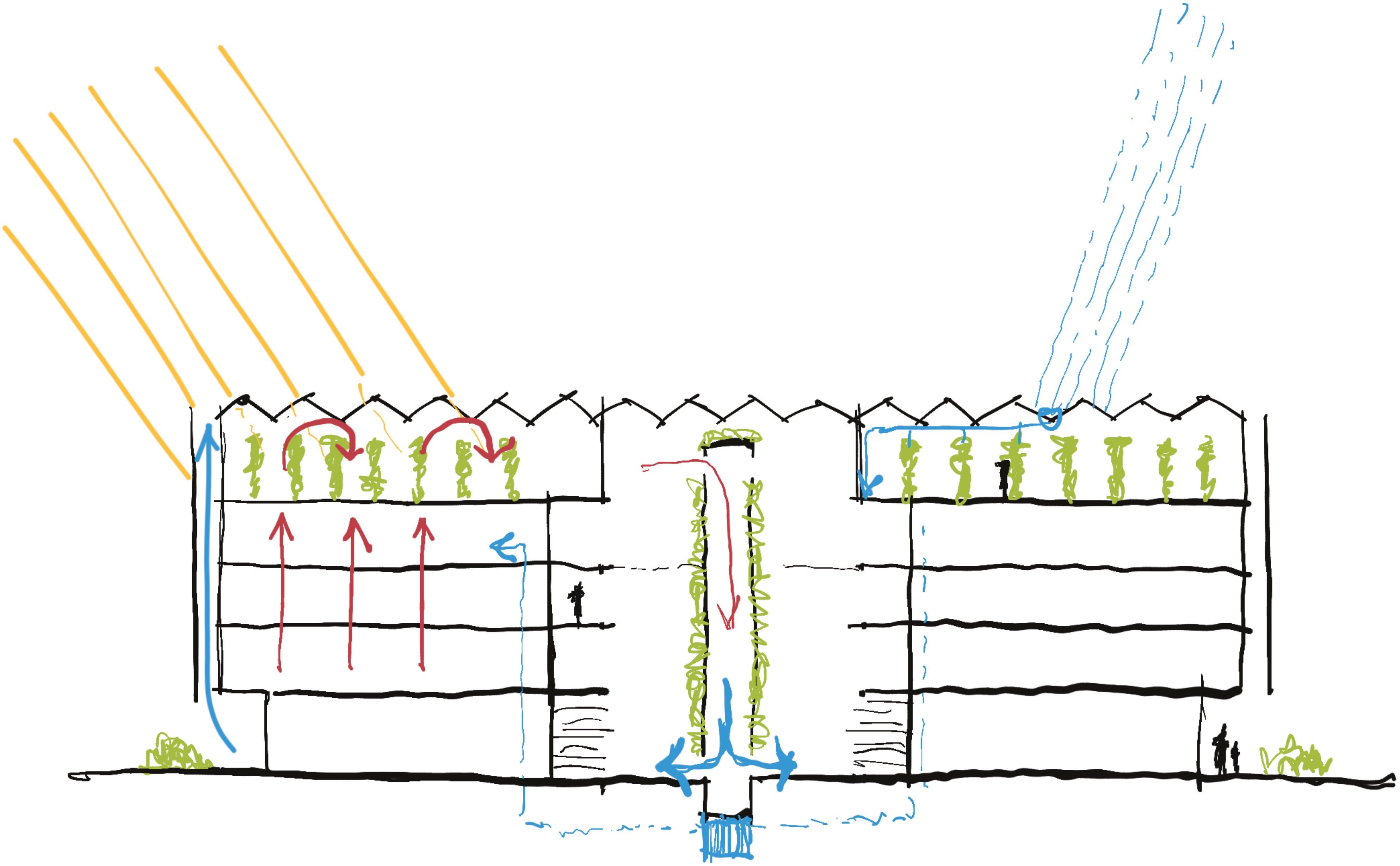


Fig 5.1: MicroArcology

between human and plant occupants, along with the adaptation to the site and climate, will contribute to a sustainable and comfortable living and working environment.

The arcology, a portmanteau of architecture and ecology, was a concept introduced by Paolo Soleri in the 70s which imagined a city modeled after a natural ecology. Fundamental to this model was the concept of a food energy nexus, which seeks to consolidate where food is produced and where it is consumed.

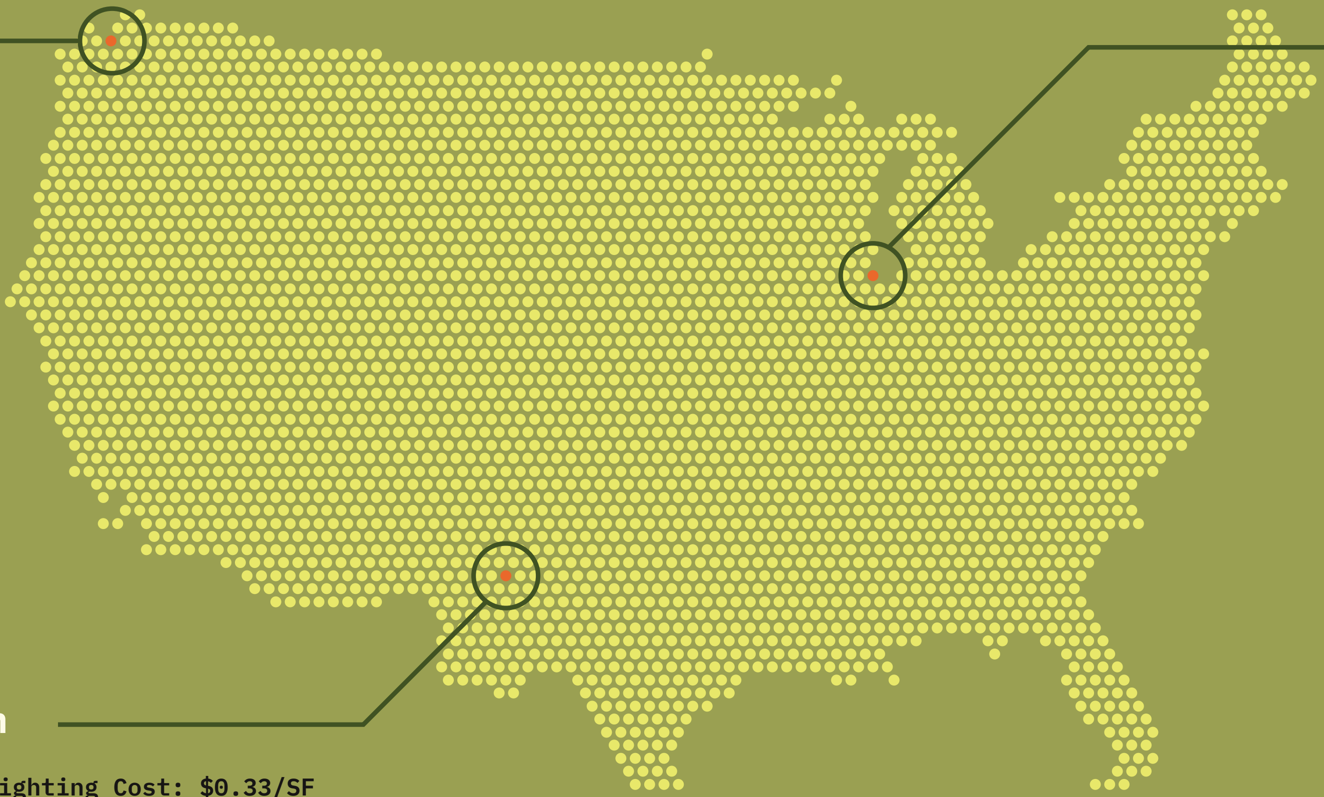
While Soleri imagined the arcology on the urban scale, there is an opportunity for applying the paradigm at the building scale, where the integrated greenhouse becomes the organizational factor for how the building connects to the surrounding environment. This is a shift away from Le Corbusier's ideas of a building as a machine for living and re-imagines the building as a symbiotic extension of an integrated ecosystem that is generative, rather than harmful, to the health of the system (Zari, 2018).

One hallmark of natural ecosystems is resiliency, which permits them to adapt to abrupt changes while sustaining the organisms within the system; failure to understand how ecosystems work at a systematic level often leads to a shallow translation into the built environment that fails to address underlying issues (Zari, 2018), as is the case with Acrosanti, Soleri's attempt at an arcology on an urban scale.

When developing a new paradigm for how a building might interact with its surroundings, it is useful to first identify values shared by natural systems. These values in no way ascertain a successful interpretation of an ecological system at the building scale, but rather serve as the framework for a mode in the examination into ways in which the building may be understood in new ways. According to Etxeberria et al. (2017), natural systems observe the following:

> Nature runs on sunlight
> Nature uses only the energy it needs
> Nature fits form to function
> Nature recycles everything
> Nature rewards cooperation
> Nature banks on diversity
> Nature demands local expertise
> Nature curbs excesses from within
> Nature taps the power of limits

With these guidelines in mind, the concept for a new building typology begins to emerge, not a sprawling environmental complex, but something smaller, originating from the context of its surroundings. Not so much a building as an environmental adaptation: a MicroArcology.



Seattle

Annual Lighting Cost: $0.52/SF
Annual Heating Cost: $111,873
Max BTU: 2,087,205

Total = $123,417

Chicago

Annual lighting cost $0.45/SF
Annual Heating cost: $192,696
Max BTU: 3,709,174

Total = $202,686

Tucson

Annual Lighting Cost: $0.33/SF
Annual Heating Cost: $37,035
Max BTU: 1,967,169

Total = $44,361

Fig. 5.2: Climate Selection

5.2 Climate Selection

The impact of climate on greenhouse performance can vary significantly depending on the location. In order to test an applied design, three different climates—Chicago, IL, Seattle, WA, and Tucson, AZ—were simulated with the test greenhouse to examine the implications for heating, cooling, and lighting requirements in each location.

Chicago, IL

Chicago experiences a continental climate with cold winters and hot summers. In this climate, heating during winter is a primary concern. The greenhouse will require a heating system to maintain a stable growing environment, especially during the colder months. The cost of heating can be quite high due to the extended duration of cold weather. Additionally, the greenhouse will also require cooling during the hot summers, which may include ventilation systems, shading, or evaporative cooling. Lighting may be required to supplement natural sunlight during the shorter winter days. The cost of lighting will depend on the duration and intensity required.

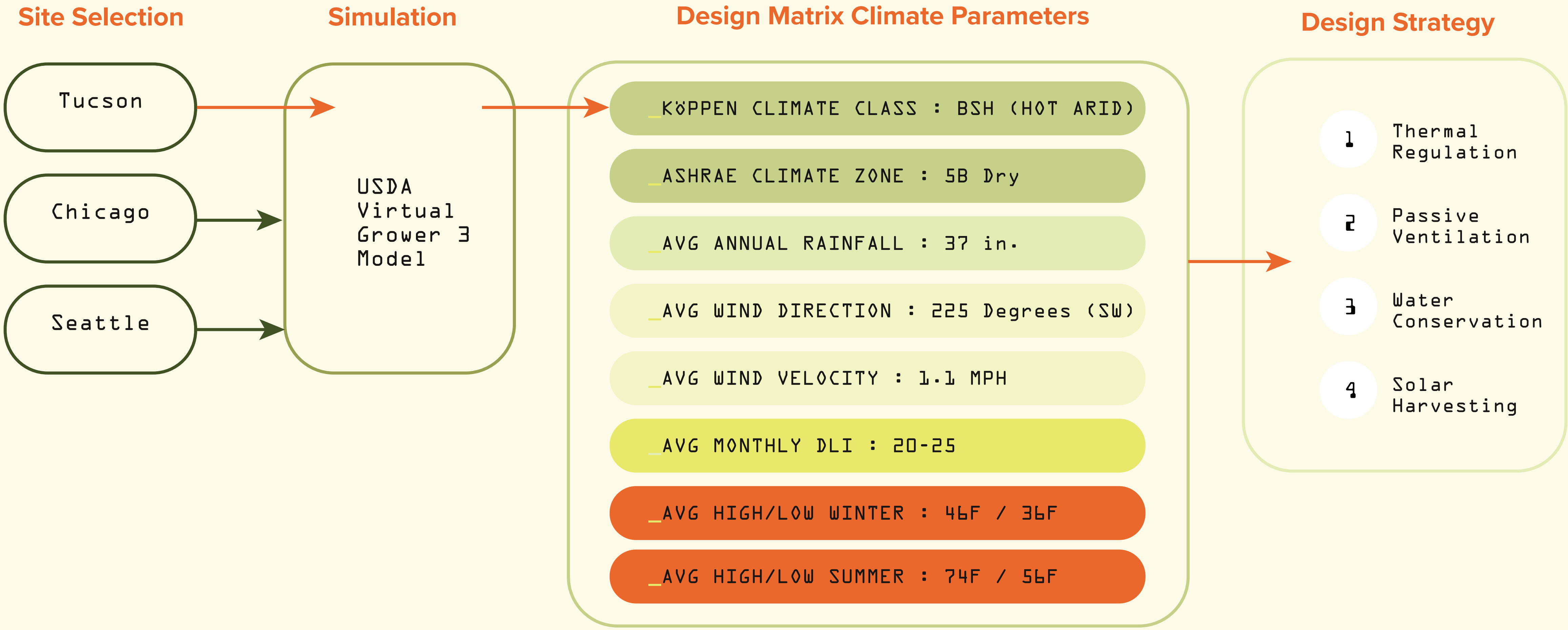
Seattle, WA

Seattle has a marine west coast climate characterized by mild, wet winters and cool, dry summers. The climate in Seattle is relatively moderate compared to Chicago. The greenhouse will still require heating during the winter months, although the duration and intensity of heating may be less compared to Chicago. Cooling requirements may be minimal due to the mild summers. Natural ventilation and shading techniques might be sufficient to manage the temperature. Seattle receives a fair amount of cloudy days throughout the year, which can impact the availability of natural sunlight for plant growth. Therefore, the cost of lighting to supplement sunlight may be higher than in some other locations.

Tucson, AZ

Tucson has a desert climate with extremely hot summers and mild winters. In this climate, the primary concern is cooling rather than heating. The greenhouse will require effective cooling systems to combat the intense heat, such as evaporative cooling or shade structures. Cooling costs can be significant due to the long duration of hot weather. In contrast, heating requirements may be minimal during the relatively mild winters. Tucson benefits from ample sunshine throughout the year, which reduces the need for supplemental lighting.

Overall, the cost of running a greenhouse in each of these climates can vary due to different heating, cooling, and lighting needs. Chicago will have higher heating costs, Seattle may have higher lighting costs, and Tucson will likely have higher cooling costs. The specific costs would depend on factors such as the size of the greenhouse, insulation levels, energy efficiency of the systems used, and local energy prices, demonstrating the impact a single factor such as climate can have on long term performance of a greenhouse, as well as shed some light on potential advantages to developing symbiosis with an existing building that might offset certain costs in certain regions.



Site Selection

Tucson

Chicago

Seattle

Simulation

USDA
Virtual
Grower 3
Model

Design Matrix Climate Parameters

_KÖPPEN CLIMATE CLASS : BSH (HOT ARID)

_ASHRAE CLIMATE ZONE : 5B Dry

_AVG ANNUAL RAINFALL : 37 in.

_AVG WIND DIRECTION : 225 Degrees (SW)

_AVG WIND VELOCITY : 1.1 MPH

_AVG MONTHLY DLI : 20-25

_AVG HIGH/LOW WINTER : 46F / 36F

_AVG HIGH/LOW SUMMER : 74F / 56F

Design Strategy

1. Thermal Regulation
2. Passive Ventilation
3. Water Conservation
4. Solar Harvesting

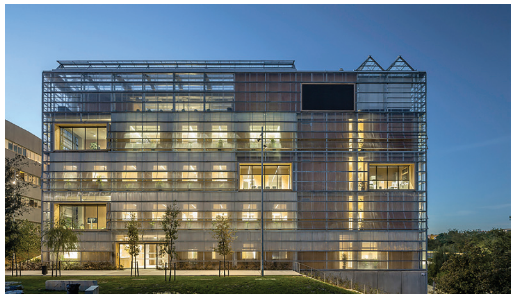
Fig. 5.3: Feasibility Study

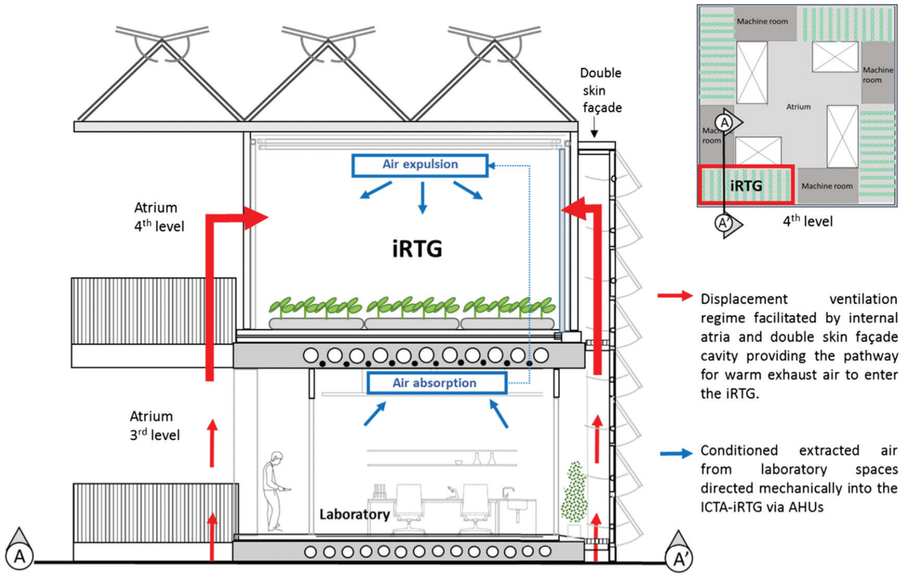
5.3 Feasibility Study

Tucson, AZ

Tucson is already established as a greenhouse agriculture producer. Sales of nursery, greenhouse, floriculture, and sod in Pima county rank third in state and top 7% in total US counties producing these products (Arizona Dept. of Agriculture, 2018). Tucson is ideally suited for glasshouse growing of warmer climate plants such as tomatoes & cucumbers.

Tucson has a similar climate to Barcelona, Spain, which features a well-supported precedent integrated greenhouse design in the ICTA-ICP building, using vents and fans to control hot summer temps. However, the lack of greenhouses in this climate is not due to hot summer temperatures (lack of development of greenhouse technology is the low cost and availability of hand labor from migrant workers. This has led to investments in growing technology, rather than greenhouse structure and climatic control, which stand to offer significant energy savings and temperature control for greenhouses if applied).





Displacement ventilation regime facilitated by internal atria and double skin façade cavity providing the pathway for warm exhaust air to enter the iRTG.

Conditioned extracted air from laboratory spaces directed mechanically into the ICTA-iRTG via AHUs

Fig. 2. Three main flow paths for heat exchange between the ICTA building and the iRTG.

Table 1
Operational characteristics of ICTA building.

Building mode	Season	Date	Heating or cooling
1 - Winter	Winter	1 Dec. - 31 Mar.	Yes
2 - Intermediate A	Spring	1 Apr. - 31 May.	No
3 - Summer	Summer	1 Jun. - 30 Sept.	Yes
4 - Intermediate B	Autumn	1 Oct. - 30 Nov.	No
5 - Passive mode	Weekends and holidays	All year	No
Laboratories	All year	Depends on ongoing research	Depends on ongoing research

Fig. 5.4: ICTA-ICP Building

5.4 Climate Precedent

ICTA-ICP Building, Barcelona // UAB H Arquitectes + DATAAE

The ICTA-ICP Building in Barcelona, designed by UAB H Arquitectes in collaboration with DATAAE, combines sustainable design principles, environmental adaptation, and an integrated agricultural element within a semi-open concept.

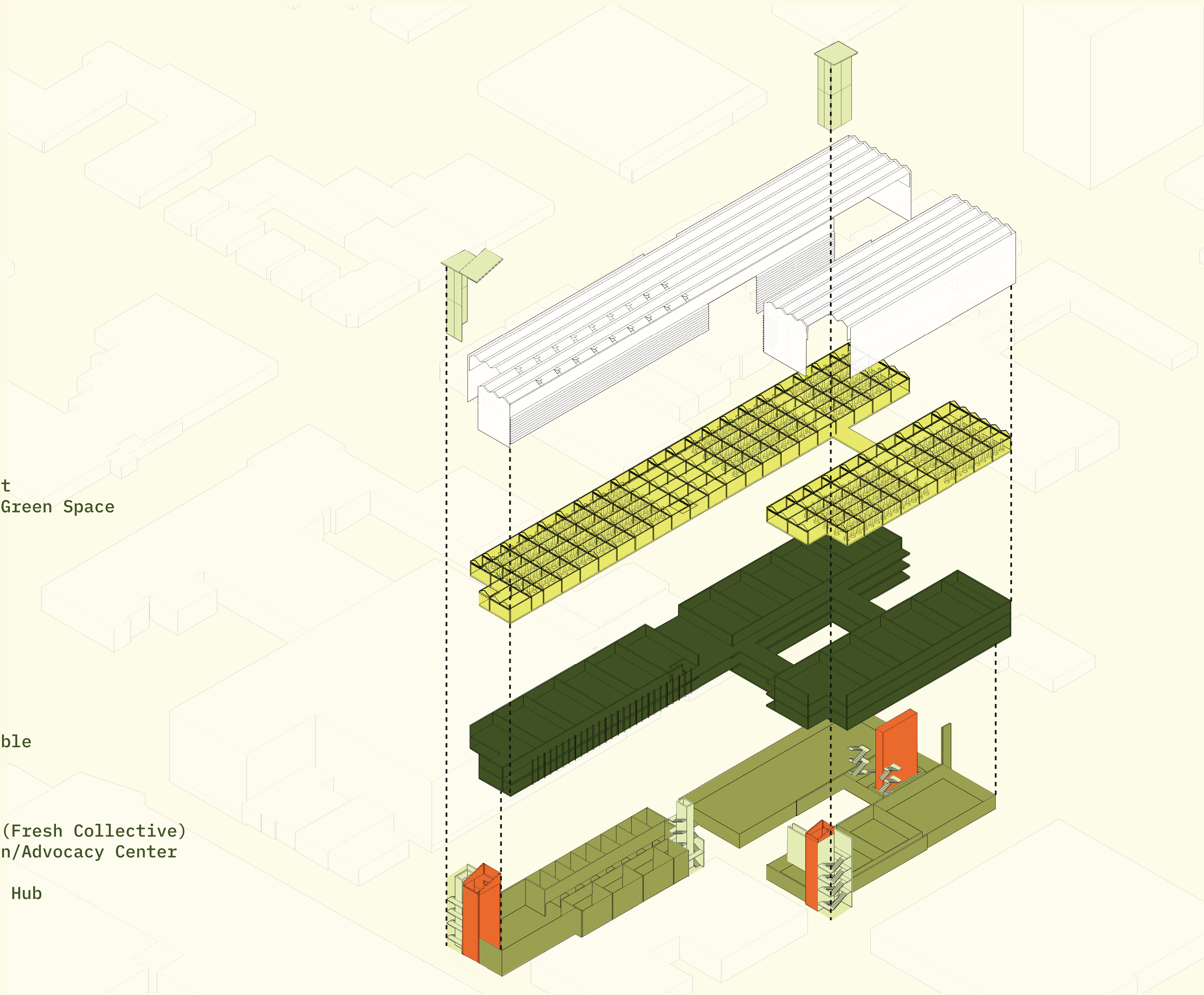
The building serves as the headquarters for the Institute of Environmental Science and Technology (ICTA) and the Catalan Institute of Paleontology (ICP), which are part of the Autonomous University of Barcelona. The design focuses on creating a space that fosters interdisciplinary research, collaboration, and environmental consciousness.

The ICTA-ICP Building utilizes several strategies that make it a stand out precedent for an integrated agricultural design. It incorporates passive design techniques like solar orientation and natural ventilation to reduce energy consumption, and is positioned to take advantage of natural light, optimizing daylighting and reducing the need for artificial lighting. The facade features adjustable louvers that provide shading during warmer months, reducing heat gain and maintaining a comfortable indoor environment while allowing light to penetrate the envelope, serving both people and plant occupants.

The building also incorporates sustainable materials and technologies. It has a high-performance thermal envelope that enhances insulation and minimizes energy loss. Solar panels are installed on the roof, generating renewable energy to power the building. Rainwater harvesting and a greywater recycling system are implemented to reduce water consumption.

However, possibly the most notable feature of the ICTA-ICP Building is its integration of an agricultural component. The architects introduced green spaces and vertical gardens throughout the building, including a rooftop greenhouse which opens to a central atrium leading down to ground level. These areas serve multiple purposes: they enhance the building's aesthetics, provide spaces for relaxation and social interaction, and contribute to the overall environmental performance of the structure. The inclusion of plants helps improve indoor air quality by filtering pollutants and adding oxygen while simultaneously fostering a connection with food and nature, promoting a sense of well-being among the building's occupants with the added benefit of food production.

The ICTA-ICP Building in Barcelona demonstrates a sustainable and environmentally responsive design approach. The design not only adapts to the surrounding environment via passive design strategies but also incorporates agricultural elements that enhance the building's functionality, aesthetics, and overall spatial experience. By systematically integrating the ability grow food in the space, the project serves as a model for future environmentally conscious designs which serve a range of occupants and balance the needs of both plants and people.



Site: 51,973 SF
- 34,740 SF Building Footprint
- 5,000 SF Outdoor Community Green Space

🟨 **RTG: 33,500 SF**
- 30,000 SF Growing Area
- 3,000 SF Seeding/Prep
- 500 SF Office
- Freight Elevator

🟩 **Housing: 127,000 SF**
- Blended Market Rate/Affordable

🟩 **Retail: 35,440 SF**
- 12,000 SF Community Market (Fresh Collective)
- 3,600 SF Ag Worker Education/Advocacy Center
- 5,500 SF Restaurant
- 3,000 SF Local Distribution Hub
- 8,800 SF Retail Shops
- 1,100 SF Micro Shops
- 1,440 SF Circulation

🟩 **Circulation**

🟧 **Cooling Towers**

Fig 5.5: Program Development

5.5 Program Development

The MicroArcology is designed to accommodate a diverse range of functions that foster a symbiotic relationship between agriculture, retail, and housing. The program for the building comprises several key components, each serving a specific purpose to create a vibrant and self-sustaining community.

The rooftop greenhouse space, spanning 33,500 square feet, forms the heart of the MicroArcology. This controlled environment is dedicated to cultivating a variety of plants, utilizing advanced agricultural techniques to maximize productivity. It serves as a local source of fresh produce, supplying the community market on the ground level with a steady and reliable stock of high-quality fruits, vegetables, and herbs.

The ground level retail area, covering 35,440 square feet, encompasses multiple functions that revolve around the concept of a community market. Within this space, a restaurant is established, which not only benefits from the rooftop greenhouse's produce but also creates a farm-to-table experience for visitors. The restaurant showcases seasonal and locally sourced ingredients, providing a unique dining experience and fostering a deeper connection between consumers and their food sources.

In addition to the restaurant, the ground level includes a distribution hub that supports other farmers in the area. This hub acts as a central gathering point where local farmers can bring and share their agricultural products, fostering collaboration and strengthening the regional food system. To complement the market and restaurant, a collection of retail shops and micro shops is integrated, offering a variety of products that support and enhance the overall retail experience.

The upper floors of the MicroArcology are dedicated to blended market rate/affordable housing, spanning 127,000 square feet across three floors. These floors provide a range of housing options to accommodate people of different income levels, including the farmers and workers from the rooftop greenhouse. The intention is to create a diverse and inclusive community where residents can live and interact, fostering a sense of belonging and shared responsibility.

The design of the building promotes interaction and collaboration among its occupants. The integration of the rooftop greenhouse, ground-level retail, and housing creates a seamless flow of activities, allowing residents, visitors, and workers to intermingle and form connections. The presence of the community market not only supports local agriculture but also acts as a social hub where people can come together, exchange ideas, and strengthen community bonds.

Overall, the MicroArcology serves as a multi-functional space that embraces sustainability, community engagement, and healthy living. By integrating agriculture, retail, and housing in a harmonious manner, it creates an environment where people can thrive, access fresh and locally sourced food, and actively participate in shaping their community.

Thermal Regulation	Dual-Skin Bio-climactic Facade	Passive Heat Recovery	Ground Cooling System
Passive Ventilation	Ridgeline Ventilation	Katabatic Cooling Towers	
Water Conservation	Aeroponic Growing Towers	Closed Recirculating Irrigation	Residential Greywater Recycling
Solar Harvesting	Rooftop Greenhouse	South PV Wall	

Fig. 5.6: Design Strategies for Building Performance

5.6 Design Strategies

Several responsive design strategies are implemented to address the challenges of the hot, dry, arid climate of Tucson. These strategies focus on thermal regulation, passive ventilation, water conservation, and solar harvesting, ensuring the building's sustainability and comfort while balancing the needs of plant and human occupants.

Thermal regulation is achieved through the application of a dual-skin bioclimatic facade. The outer skin provides shading and reduces solar heat gain, while the inner skin acts as insulation, reducing heat transfer. This design feature helps maintain comfortable indoor temperatures and reduces the need for mechanical cooling. Additionally, passive heat recovery systems capture and redistribute excess heat generated within the building, minimizing energy waste and improving overall energy efficiency. A ground cooling system, utilizing geothermal energy, helps further regulate indoor temperatures by circulating cooler air through underground pipes, reducing the reliance on traditional cooling methods.

Passive ventilation techniques are employed in the rooftop greenhouse and throughout the building. Ridgeline ventilation in the greenhouse allows hot air to escape, facilitating natural airflow and preventing excessive heat buildup. Katabatic cooling towers, positioned at either end of the building, take advantage of the prevailing winds to draw cool air into the structure, promoting natural ventilation and enhancing the comfort of the interior spaces.

Water conservation measures are integrated into the building's design, particularly in the agricultural area. Aeroponic growing towers are utilized, significantly reducing agricultural water consumption by delivering water and nutrients directly to plant roots in a highly efficient manner. Closed recirculating irrigation systems further minimize water waste by collecting and reusing excess water. Moreover, greywater recycling systems are implemented to collect and treat wastewater from residential and retail areas. This treated greywater is then reused for non-potable purposes, offsetting the demand for freshwater resources.

Solar harvesting plays a crucial role in the MicroArcology's energy sustainability. The design of the rooftop greenhouse incorporates transparent or translucent materials, allowing natural sunlight to penetrate and nourish the plants. This design also maximizes the utilization of solar energy for the growth and cultivation of crops. Furthermore, a south-facing photovoltaic wall is integrated into the central circulation atrium, harnessing solar energy to generate electricity for the building's needs, reducing reliance on the grid and promoting renewable energy generation.

By incorporating these responsive design strategies, the MicroArcology effectively addresses the specific challenges of its arid climate. These strategies contribute to thermal comfort, energy efficiency, water conservation, and renewable energy generation, creating a sustainable and environmentally conscious building that harmonizes with its surroundings.

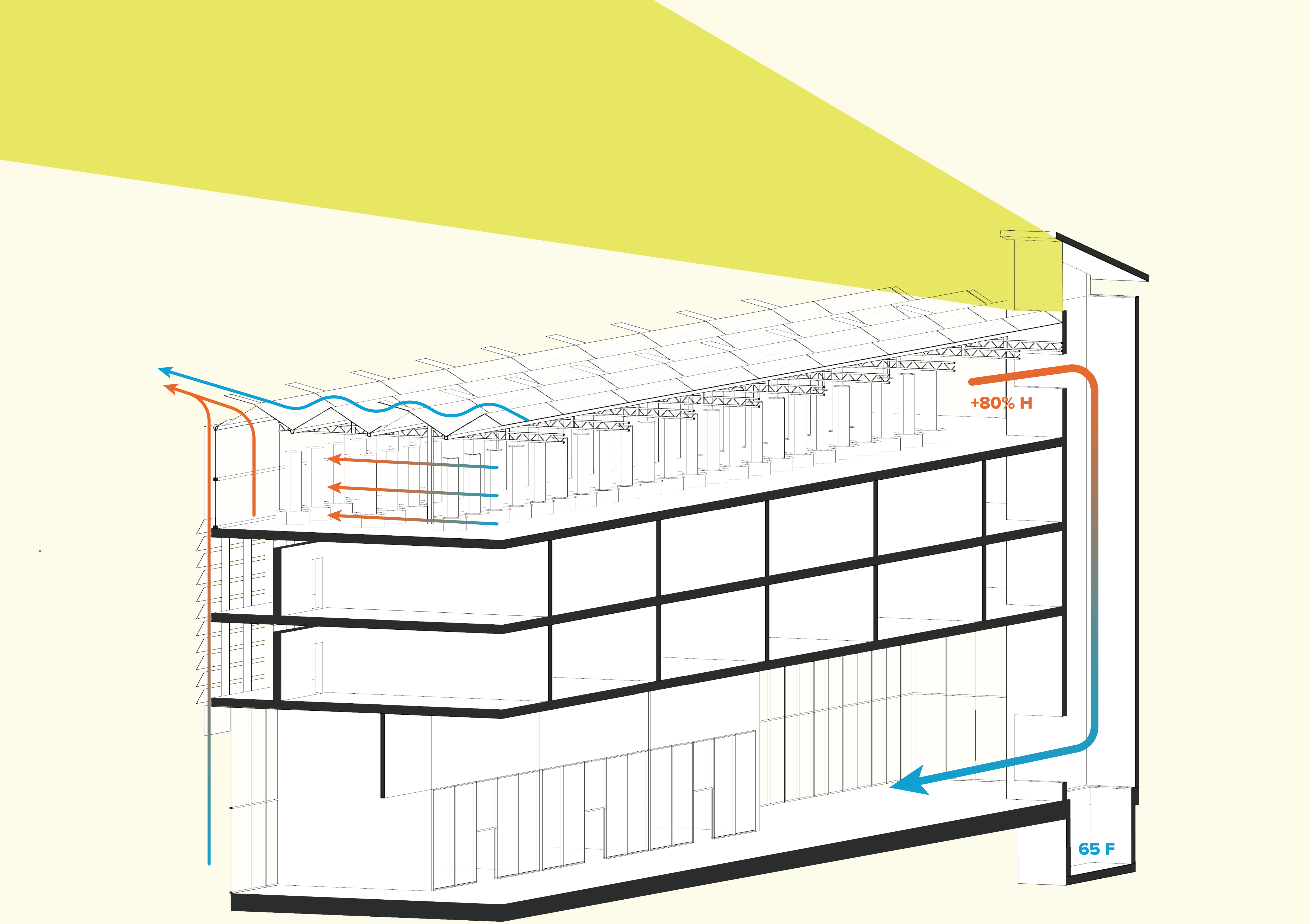


Fig. 5.7: Katabatic Cooling Towers

Katabatic Cooling

Katabatic cooling towers, strategically positioned at either end of the MicroArcology, play a crucial role in naturally regulating the interior building temperature during the hot summers. These towers take advantage of the phenomenon known as katabatic winds, which are cool, dense air currents that flow downhill due to the force of gravity.

As the towers are situated at higher elevations, the cooler air naturally descends and is drawn into the building through openings at the base of the towers. The incoming cool air replaces the warmer air inside the structure, creating a natural ventilation effect.

This process facilitates the removal of heat and helps to cool the interior spaces without relying solely on mechanical cooling systems. The katabatic cooling towers harness the power of nature to enhance thermal comfort and energy efficiency within the MicroArcology, providing a sustainable solution for temperature regulation in the hot Tucson summers.

Passive Heat Recovery

The rooftop greenhouse of the MicroArcology benefits from a passive heating system that maximizes energy efficiency and promotes plant growth, a process that has recently gained been explored as a symbiotic exchange between greenhouse and host building (Mireia et al., 2017; Goldstein, 2016). During the winter months, when heating is required, the residential floors below naturally generate heat through human occupancy and other activities.

This excess heat is intelligently ventilated and redirected into the greenhouse space. As the warm air rises, it is channeled through a system of vents and ducts, transferring it to the greenhouse. By utilizing this passive heat recovery mechanism, the greenhouse benefits from a steady flow of

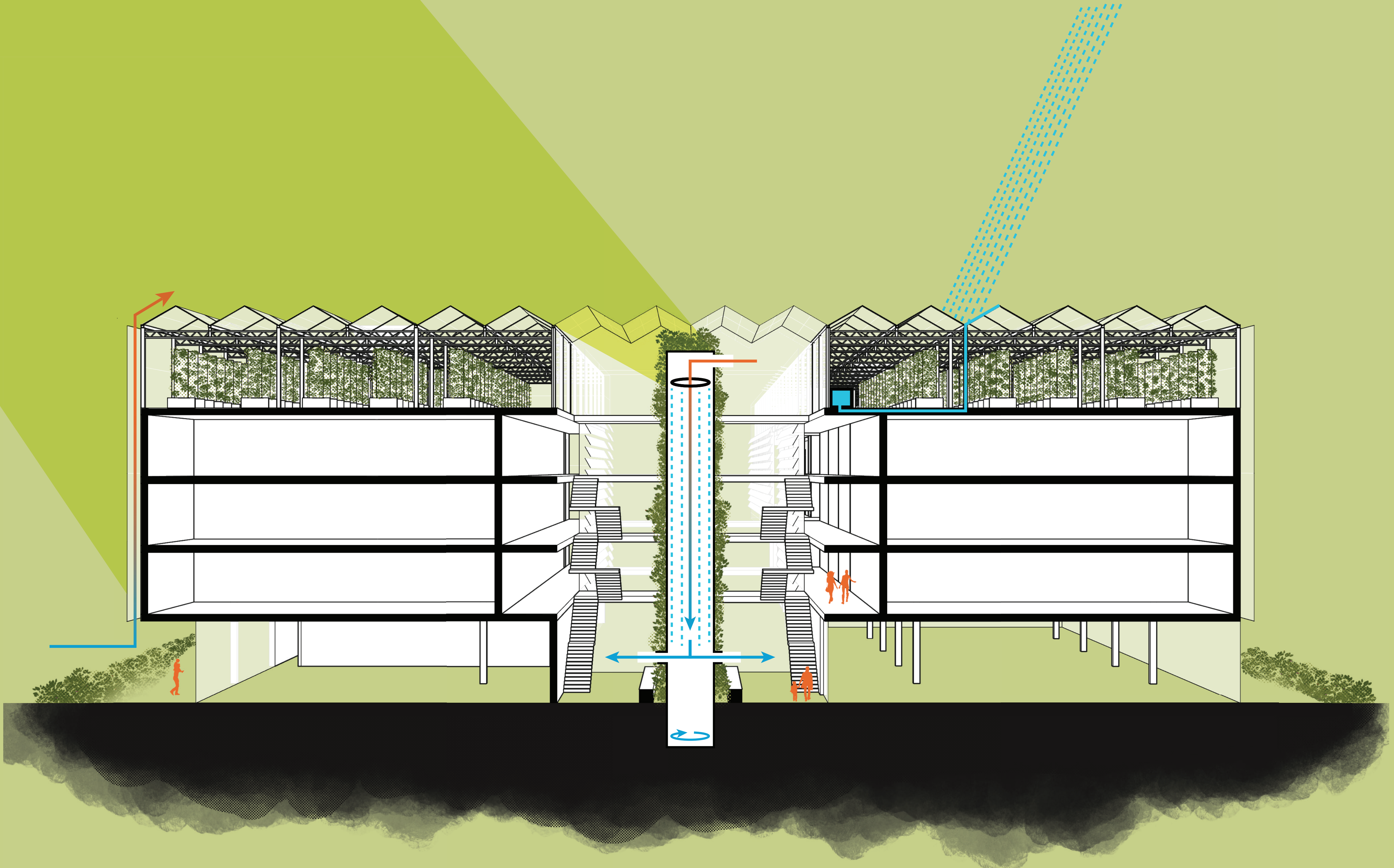


Fig. 5.8: South Atrium Section

prewarmed air, maintaining optimal temperatures for plant growth. Additionally, the ventilated air from the residential floors is rich in CO2, which is essential for photosynthesis. This symbiotic exchange ensures that the greenhouse receives the ideal combination of warmth and CO2, creating an environment where plants can thrive while effectively utilizing the waste heat generated by the building below.

Aeroponic Tower Gardens

The rooftop greenhouse incorporates the use of aeroponic tower gardens, a highly efficient method of cultivating plants that offers significant water conservation benefits while maximizing access to daylight. Aeroponics involves growing plants without soil, where nutrient-rich water is misted onto the roots suspended in the air. In the context of tower gardens, multiple vertical towers are utilized, creating a compact and space-efficient arrangement for plant cultivation. This system allows for precise control over water usage, as the misting process delivers water directly to the roots, minimizing wastage and evaporation.

By implementing aeroponic tower gardens, the MicroArcology's rooftop greenhouse can achieve substantial reductions in water consumption compared to traditional soil-based agriculture (Lakhiar, 2018). Furthermore, the vertical arrangement of the tower gardens optimizes the distribution of natural light, ensuring that each plant receives ample exposure to sunlight throughout the day.

This combination of water efficiency and enhanced daylight utilization creates an ideal environment for plants to thrive, maximizing productivity while minimizing resource consumption. In a location like Tucson, where arid temperatures make water conservation a top priority, shifting agriculture to a controlled environment for reduced water consumption, with rates as high as 98% in some conditions (AlShrouf, 2017).

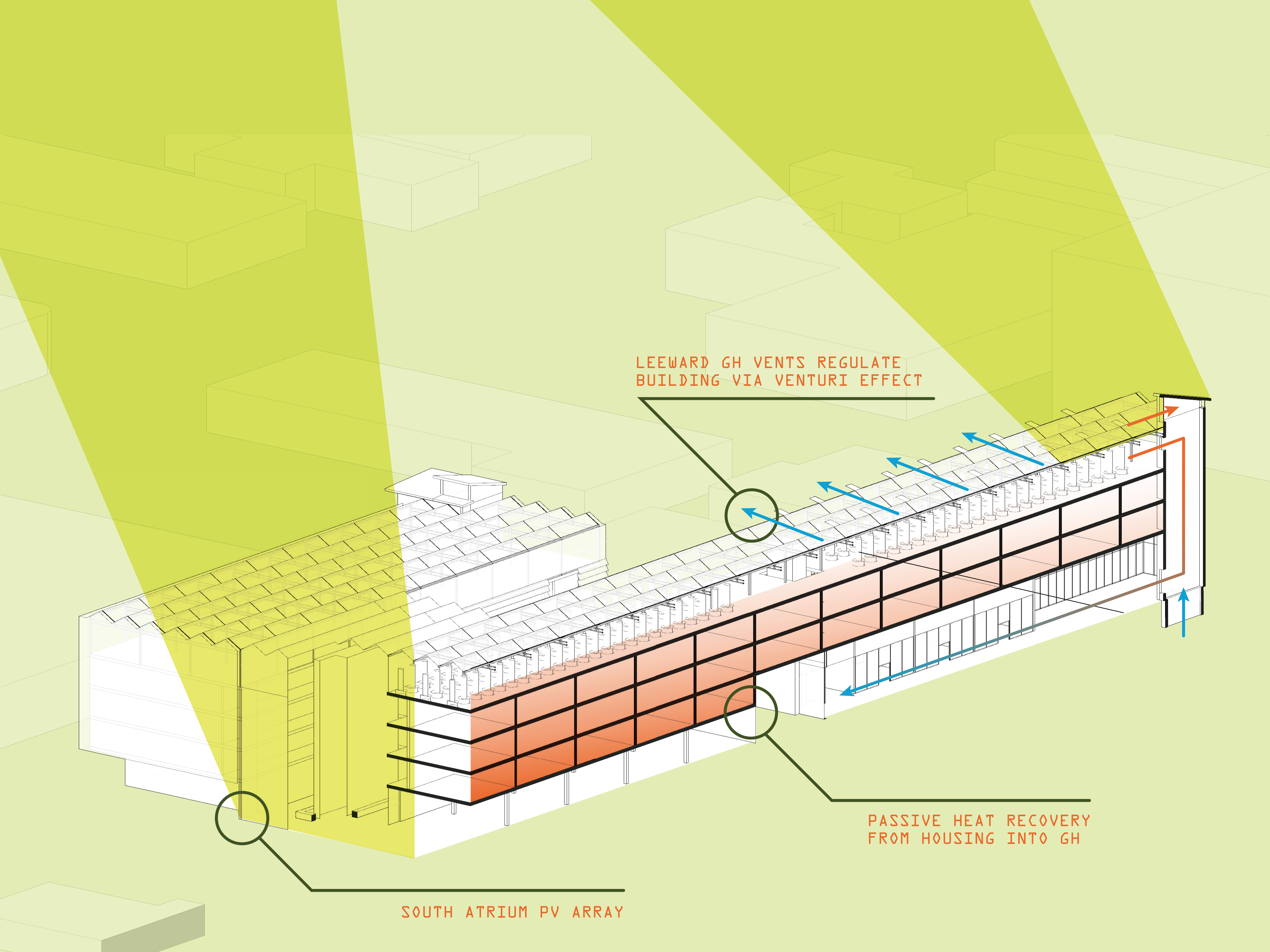


Fig. 5.9: Passive Ventilation

Balancing Needs

This project uses the design framework to develop a building concept oriented around climate-responsive, integrated design emphasizing shared resource flows between a building and a sizable CEA component. Through the selection of design strategies, it immediately became clear that this is a framework and not a calculator. It doesn't solve design challenges - on the contrary, it actually demands more of the space through the introduction of plants - but rather acts as a rule for measuring design decisions.

For the MicroArcology, balancing the four main approaches of thermal regulation, passive ventilation, water conservation, and solar harvesting would look different should the site selected have been located in Chicago or Seattle. These are drastically different climates with different needs, so what works for one location does not necessarily translate to the other. This brings up a secondary challenge within integrated agriculture, which is the lack of precedents. Often, building strategies in architecture are not directly measured in the design process, but rather assessed after construction to gain feedback on the impact and effectiveness of the decisions. This works well for traditional building designs, but when an agricultural element is introduced, given the lack of precedents it can be difficult to make an informed decision with no point of reference to gauge expectations for the outcome. This is compounded even more when building resource flows overlap with greenhouse resource flows, compounding the ability to accurate assess either.

In light of this consideration, until we have better tools for testing the potential impact of design decisions before carrying them out on a building, balancing the needs of plants and people across a range of strategies, such as the ones outlined in this design project, will help further inform future integrations.

VI. Findings

Assessing Impact

Assessing Impact

Part VI: Findings

6.1 Defining Value

One of the challenges that arose from the design project was the question of value. Greenhouses are expensive, and the question of economic value is typically one of the first questions to be addressed when discussing value. The average time for a traditional freestanding CEA greenhouse to obtain profitability is seven years; there is no evidence to indicate that an integrated version of the same greenhouse would perform any less than its freestanding counterpart, and there is strong support to indicate by sharing resource flows with a host building would lower the cost of heating, which could reduce the window to profitability, although this would require modeling to validate.

The issue of economic value is not the only method for finding value in an integrated greenhouse; while important, economic development is only the entry point to the deeper layers of value creation which can be uncovered through the work of this thesis. By understanding the integration of a greenhouse into a building as more than a way to generate revenue, the issue of economic value actually gains complexity. While monoculture is an oversimplified natural system, the addition of a polyculture cropping into an urban integrated greenhouse demonstrates the willingness to forgo optimized efficiency in exchange for reduced food miles, and greater flexibility for locally preferred plant products, and variable nutrient density.

The topic of nutrient density is a consistent theme in the discussion of value, as there is currently no standardized metric for assessing the impact of nutrient dentistry in a given space. There is a likely a considerable difference in the nutritional value of a pound of romaine lettuce versus a pound of spinach, as well as a marginal difference in the space it takes to produce those two products in the same time frame. In order to truly understand the impact of nutrient density, the scope of this work would need to expand to include agricultural experts. For now, it is merely important to recognize that not all plants offer the same density, and density itself is not currently the main driver in production, but market needs. The entrance of agriculture into the urban environment offers an opportunity to explore new ways of assessing this.

6.2 Labor & Resource Flows

Following the application of the a design framework, it's clear that integrating a greenhouse into a project demands significant effort to balance multiple occupant needs. In light of this delicate balance, it's understandable why research mentioning integrated agriculture frequency cites metabolism as a critical issue surrounding the future evolution of CEA (Caprotti, 2013; Appolloni, 2021; Choi, 201; Parada, 2021, to name a few). Taking the MicroArcology as a proof of concept, it's evident that a few levels of metabolic activity energy from this type of intensive process. While the MicroArcology represents a responsive building design with an integrated agricultural component, it also demonstrates metabolism on three interconnected levels: ecological metabolism, social metabolism, and individual metabolism. Labor is connected to all of these, although it's most understood at the human scale.

Ecological Metabolism	Biodiversity & Microclimate Development
Social Metabolism	Generative Labor
Individual Metabolism	Food Consumption & Waste Recapture

Fig 6.1: Metabolic Flows

Ecological metabolism is manifested in the building's engagement with its surrounding environment. The rooftop greenhouse, with its diverse plant life, contributes to the consumption and resource flows that support biodiversity and microclimate development. Through the cultivation of a variety of plant species, the greenhouse fosters ecological balance, attracting beneficial insects, promoting pollination, and enhancing the local microclimate. The integration of green infrastructure, such as the katabatic cooling towers and ground cooling system, further interacts with the natural elements, utilizing passive cooling strategies and reducing energy demand.

Social metabolism is demonstrated in the movement of resources within the MicroArcology and its connection to the larger community. The generative labor involved in the rooftop greenhouse's cultivation and the subsequent distribution of produce to the on-site market, restaurant, and other retail spaces creates a self-sustaining ecosystem. This dynamic resource flow from the agricultural component to the commercial and residential areas exemplifies the interdependence of various social and economic activities within the building. The MicroArcology serves as a hub for local farmers, fostering collaboration and enabling the sharing of agricultural products, reinforcing a sense of community and sustainable economic practices.

Individual metabolism is tied to localized food consumption and water recapture. The availability of fresh produce from the rooftop greenhouse promotes healthier eating habits among residents, retail customers, and restaurant patrons. The emphasis on sustainable water management, such as greywater recycling and closed recirculating irrigation, encourages responsible water usage and reduces reliance on external water sources. This localized approach to food production and water conservation empowers individuals to take an active role in their own metabolism, promoting self-sufficiency and resilience within the built environment.

By embodying ecological, social, and individual metabolism, the MicroArcology demonstrates a holistic and regenerative approach to building design. It creates a symbiotic relationship between the built environment and its surroundings, fosters community engagement and sustainable economic practices, and empowers individuals to make conscious choices regarding their consumption and resource utilization.

This is taking that idea of a building as a metabolic gift, and expanding it across multiple scales. This issue is complex enough, it's can't be only addressed on a building level. That's important, but for me, it's more the starting point of entry into a much larger set of possibilities centered around this idea that an environment is self regulating via the metabolic process, so how can we address this. It starts at an individual scale, or it will end at the ecological one.

VII. Conclusion

Built to Grow

Built to Grow

Part VII: Conclusion

6.1 Summary

The work of this thesis serves two primary purposes, each defined by a corresponding deliverable. The first is the need for an entry point into building integrated agriculture that consolidates the best practices in greenhouse design and condenses them into a coherent body of work. The literature review provided the foundation for this body of work, synthesizing the varying fields of research around greenhouses into factors relevant to design and integration from a built environment perspective. The result of the literature review indicated a strong need for design support in order to integrate greenhouses into buildings, and from this body of information, a conceptual framework was developed to serve as a guideline for greenhouse integration.

However, design is an active process and having a body of knowledge with no way to apply it framed the second task of this work: the development of an integrated design matrix that could serve as a tool for assessing a potential greenhouse integration into a new building project.

6.2 Contributions

There is currently no comprehensive resource on greenhouse integration specific to architects and designers in the built environment. This work provides an overview of the current literature on greenhouses, identifying the shared factors between greenhouse design and building design. These factors were defined individually as discreet elements and then organized in proximity to similar factors until a framework demonstrating the relationship between the parts and the whole provided two scales of understanding as both individual systems and the larger connected greenhouse as a whole.

From this framework, an integrated design matrix was developed to provide an applied method for assessing a potential integrated greenhouse design, bridging the gap between research and practice. This tool is not comprehensive but rather serves as a starting point for addressing the needs of an integrated greenhouse in the context of climate, plant selection, and host building.

6.3 Future Research

As a result of the applied design project, one thing that became immediately clear is the need for better tools to assess greenhouse performance in the context of the built environment. The role of simulation was significant factor in greenhouse design and a topic that emerged frequently from the literature reviewed; however, these tools were typically industry specific to either greenhouse manufacturers, engineers, or horticulturalists. As it stands, many of the proposed integrations selected as a result of the design framework are not capable of being easily tested by architects and designers. This is especially true regarding plant lighting, which is measured as PPFD and only usable to plants in the 400-700nm range, known as PAR. Given that light is the primary factor when considering greenhouse design, the inability to simulate light performance for the plants inside the proposed space brings into question all the other decisions that follow. Sure, a greenhouse could potentially operate solely on supplemental electric lighting, as is the case with indoor farms. However, these models of agriculture are rapidly proving unsustainable, and

Fig 7.1: Timeline

at the core of the design framework is the goal to develop a building as the adaptation of the surrounding environment. To make large scale design decisions that implement expensive greenhouse technology, yet offer no real way to assess the fitness of the space for plant lighting feels like a conflicting goal. With that in mind, the applied design project clarified a central need around deeper, more effective greenhouse integration. Fortunately, thanks to the tremendous support of the faculty at the University of Washington, and especially my thesis committee, I'm able to take what I learned from this project and advance it one step further, to a design tool for agricultural daylight assessment.

While a comprehensive tool capable of simulation in all areas of greenhouse performance, including lighting (daylighting and supplemental electric lighting), ventilation, heating and cooling, humidity, crop density and production cycles, and shared resources flows with a host building would be ideal, the scope of that project would be extensive. In order to bridge the gap between industry-specific tools which offer little access to architecture, the work of this thesis will narrow and specify to focus on the development of a tool for agricultural lighting simulation in the built environment.

Of all the performance factors related to greenhouses, lighting is the most important, and the largest consumer of energy. Daylighting provides the primary source of energy for plants to conduct photosynthesis, and while the needs of any given plant are well established, not all light is equal. Solar radiation entering a greenhouse is measured by three factors: quantity, quality, and duration.

Quantity is the volume of photons hitting any given surface and is directly related to plant growth. Duration, or photoperiod, is linked to plant cycles and triggers events such as flowering. Quality is a measure of the fitness of spectral light necessary for a given phase of a plant, and changes based on the growth cycle of the plant, but also has a significant impact on the outcome of the plant product and can influence flavor, color, and nutritional content depending on the range of spectral light the plant receives.

The framework and information contained in this thesis will provide a foundation for the development of a built environment-specific tool capable of simulating spectral light in a controlled environment setting. While there are tools currently available to accomplish this, none are optimized for the built environment, thus the tool will be built in Rhino Grasshopper, allowing it the ability to interface with a number of other simulation plugins on a specific model.

Additionally, there are a number of factors unique to building integrated agriculture that is not present in standard greenhouse models, including overshading from surrounding buildings in an urban setting, varying crop density zones in a polyculture greenhouse operation, vertical farming with towers, and variable materials and roof heights due to potential architectural design choices for an integrated greenhouse.

Timeline

A short note about the timeline of this thesis: this work is part of a larger project spanning both the M.Arch and M.S. Design Technology Programs. Thanks to the support of my faculty committee, I was able to plan this project as part of a concurrent degree program, allowing me to start a large scale of examination and focus on a research question, addressed in this work. However, the work does not end there, but will be continued in a narrower scope as I further develop one aspect of the conceptual framework for this issue in a more definitive resolution via development of a tool for simulation at a detailed level.

Afterword

There's Some Agriculture In My Architecture

Afterword

There's Some Agriculture in My Architecture

Design Philosophy

Architecture as Narrative

In contrast, a method provides a mode of examination; a clear mode of assessing any given topic. However rigorous, I find this process of moving back and forth between asking why we arrived at a certain way of being and how we understand that way of being to be equally important, and my process in this work reflects that fundamental paradigm.

Mythology + Methodology

Architecture is an exercise in complexity, scale, and perspective. The same could be said of storytelling, which is why I find the relationship between architecture and narrative so compelling. To explain my process, I want to frame this approach as equal parts myth and method: a myth is simply a story explaining how something in the world came to be in the current state. Collecting a group of these stories provides a mythology which serves as a valuable reference for why things are the way they are: in this case, why we do or don't farm the city, and by extension, integrated agriculture directly into our built environment on a larger scale.

Mythology + Methodology

Fig 7.2: Paradigms

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